Towards the Analysis of Transactional Software

Nicholas Kidd
Kevin Moore
Thomas Reps
David Wood

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Nicholas Kidd[1], Kevin Moore[1], Thomas Reps[1,2], and David Wood[1]

[1] University of Wisconsin; Madison, WI; USA.
{kidd,kmoore,reps,david}@cs.wisc.edu
[2] GrammaTech, Inc.; Ithaca, NY; USA.

Abstract. The computer-architecture community's recent focus on multi-core architectures has spurred renewed interest in concurrent-programming techniques and abstractions. For programmers to take advantage of the processing power of today's multi-core chips, they need to write multi-threaded applications. Specifically, the programming-language community has focused on software transactions. A software transaction declaratively specifies what program statements should execute atomically. Our research focuses on the analysis of programs that make use of software transactions. We present a novel interprocedural analysis, XRef analysis, that annotates the fields of each record type in the program with the static transactions in which it is referenced. We show how the results of XRef analysis can be used to perform additional analyses. In particular, we present two such analyses, XOrder and XProtect. XOrder is aimed at software running on a transactional-memory platform and attempts to find an optimized layout for a record in memory. XProtect is a safety analysis that warns the programmer if a shared record is inconsistently protected by a software transaction.

1 Introduction

Software developers have traditionally benefited from advances in computer architecture, which, over multiple decades, has provided a steady increase in the computing resources available to applications. However, the immense heat dissipation and power usage that results from ramping up the clock frequency has (temporarily) stalled this process.

To continue to provide software developers with increased computing resources, computer architecture has focused on thread-level parallelism. This is evident by the myriad of chip multiprocessors (CMP) in today's commodity PCs. A CMP consists of multiple processing cores on one die. Many of today's laptops now include dual-core processors. There are predictions that the next generation of processors will be 4 or 8-way CMPs.

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The CMP trend in computer architecture implies that software developers will need to write concurrent programs to take advantage of the increased processing power. In the past, the synchronization primitives used to write concurrent programs have traditionally been locks, semaphores, and condition variables. These primitives are both error-prone and do not scale to many threads of execution. Furthermore, it has been shown that this is neither composable nor effective for large data structures, such as hashtables [1].

The difficulties of lock-based programming led to research in programming with *transactions*. In abstract terms, a transaction is a sequence of events that appear to happen atomically. The idea of using transactions was borrowed from the database community. Traditional database transactions support ACID (Atomicity, Consistency, Isolation, and Durability) semantics. To avoid confusion, we will refer to transactions used in programs as software transactions.

A *software transaction* consists of a sequence of instructions executed by one thread, whose side effects appear to happen at once. Software transactions give programmers a declarative way of expressing synchronization—the programmer will specify *what* program statements are to be executed atomically and not how the atomic execution is implemented. Due to the volatile nature of memory, software transactions only concern themselves with the first three principles of database transactions, namely ACI.

Software transactions strive to facilitate the writing of correct highly-concurrent programs. By the abstract specification of atomic sections, performance of multithreaded programs can be improved by executing software transactions that operate on disjoint data in parallel. Lock-based critical sections, on the other hand, are serialized if they are protected by the same lock regardless of the data actually accessed. Additionally, programmers can leave the implementation of atomic critical sections to the underlying system.

There have been many research proposals, from both the architecture and programming languages communities, investigating *transactional memory* (TM) systems to support software transactions. These include TM systems that are implemented completely in software (STM) [2–5], in hardware (HTM) [6–10], and implementations that have various aspects implemented in hardware and software (HyTM) [11, 12]. TM systems attempt to execute software transactions concurrently. They typically enforce atomicity and isolation by stalling or aborting software transactions that conflict. A *conflict* occurs when two transactions access the same data concurrently, and one of them is a write.

While software transactions present a step forward in the evolution of concurrent programming, programmers using software transactions must still reason about program correctness and performance. Bugs may result from accesses to shared data structures that are inconsistently protected by software transactions. A program's performance can suffer if concurrency is limited by conflicting transactions. The problem of transaction conflicts can be exacerbated by transactional memory systems that detect conflicts at a coarse granularity. For example, many HTM's detect conflicts between concurrent transactions using the cache coherence mechanism. To conserve hardware resources, these systems typically detect conflicts at the granularity of a cache line. In such systems, concurrent accesses to different words in the same cache line by two different transactions can cause a *false conflict* (i.e., an unnecessary serialization of transactions that is due solely to the heuristic nature of a platform's conflict-detection mechanism—see Defn. 6). False conflicts can cause significant performance loss on HTMs [10].

To address these problems, we introduce three interprocedural dataflow analyses. The first analysis, XRef, is a static analysis that annotates the fields of each record type[3] in the program with the static transactions (Defn. 5) in which they are referenced. These (automatically inferred) annotations are important for analysis tools whose focus includes transactional software. That is, the results of XRef analysis form a basic building block on which other analyses can be built. We demonstrate this capability by implementing with our other two interprocedural analyses, XOrder and XProtect, on top of XRef.

We address false conflicts through XOrder analysis. Specifically, the goal of XOrder analysis is to reduce false conflicts among concurrent software transactions. XOrder analysis targets TM systems systems that detect conflicts at a coarse granularity. Using a detailed simulator of an HTM system, XOrder analysis more than doubled the performance for one benchmark.

XProtect is a consistency analysis. It detects when the fields of a shared record are not consistently protected by a software transaction. Inconsistencies can result in unintended program behaviors and data races.

We are (essentially) inferring annotations for the fields of record types. This allows us to ignore thread interleavings, and hence we need only perform a sequential analysis of the code from (one copy of) each separate kind of thread in the program. One way to accomplish this is to model the program with a "supermain" function that nondeterministically branches to the entry point of each kind of thread, including the `main` function.

The contributions of this paper are:

- XRef, a new software analysis that annotates the fields of a record with the static transactions in which they are accessed.
- XOrder, a software optimization that determines an optimized memory layout for the fields of a record. We measured speedups of up to 2.8.
- XProtect, a safety analysis that detects when a shared data structure is not consistently protected by a software transaction.
- Our analyses are able to analyze existing lock-based programs in a transactional setting.

The remainder of the paper is organized as follows: §2 specifies the programming model. §3 and §4 introduce the notion of a dynamic transaction and static transaction, respectively. §5 presents XRef. §6 and §7 present our additional program analyses XOrder and XProtect, respectively. §8 discusses related work.

[3] We use the term "record" to emphasize that the analysis is language independent. A record type corresponds to a C `struct` or to a class in an object-oriented language.

2 Programming Model

$$
\begin{array}{lll}
\mathit{Program} & \rightarrow & \mathit{RecordList}\ \mathit{FunList} \\
\mathit{RecordList} & \rightarrow & \epsilon \mid \mathit{RecordList}\ \mathit{Record} \\
\mathit{Record} & \rightarrow & \text{record } r_{id}\ \{t{:}id_1,\ \ldots,\ t{:}id_k\} \\
\mathit{FunList} & \rightarrow & \epsilon \mid \mathit{FunList}\ \mathit{Fun} \\
\mathit{Fun} & \rightarrow & t \text{ fun } f_{id}\ (t{:}p_1,\ \ldots,\ t{:}p_k)\ \{\ \mathit{Stmt}\ \} \\
\mathit{Stmt} & \rightarrow & t\ x \mid x = \mathit{Exp} \mid \mathit{Stmt};\mathit{Stmt} \\
 & \mid & \text{if } \mathit{Exp} \text{ then } \mathit{Exp} \text{ else } \mathit{Exp} \\
 & \mid & \text{while } \mathit{Exp}\ \{\ \mathit{Stmt}\ \} \\
 & \mid & \text{return } \mathit{Exp} \\
 & \mid & \text{begin\_transaction} \\
 & \mid & \text{end\_transaction} \\
 & \mid & \text{thread }\{\ \mathit{Stmt}\ \} \\
\mathit{Exp} & \rightarrow & n \mid x \mid x.id_j \mid \mathit{Exp}\ \mathit{op}\ \mathit{Exp} \\
 & \mid & f_{id}(\mathit{Exp}_1,\ldots,\mathit{Exp}_k) \\
\mathit{op} & \rightarrow & + \mid - \mid * \mid / \mid \mathit{lt} \mid \mathit{gt} \mid \mathit{eq} \mid \mathit{or} \mid \mathit{and} \\
t & \rightarrow & \mathit{int} \mid \mathit{boolean} \mid r_{id} \mid \mathit{void}
\end{array}
$$

Fig. 1. The source language.

Our programming model consists of a multithreaded program running on a platform that supports transactional memory. Transactional memory may be implemented in hardware, software, or a combination of the two. For XOrder analysis, we focus on TM systems that detect conflicts at a granularity larger than a memory address—for instance, at the level of a cache line. Detecting conflicts at cache-line granularity is common in HTM systems that perform conflict detection through the cache-coherence protocol [6, 8–10], in Hybrid TM systems [11, 12], and in at least one STM implementation [13]. The transactional memory system's atomicity model, either strong or weak [14], has no effect on our analyses.

For expository purposes, we use the simplified programming language specified by the grammar in Fig. 1. In the specification, n is an integer, x is an identifier, and t is a type. Fig. 1 defines a `C`-like language that includes support for Booleans, integers, records, variables, named functions, threads, and software transactions. All records are passed by reference. Fig. 2 shows an example program. Although it does not perform any meaningful task, it is intended to help clarify the capabilities of XRef, XOrder, and XProtect.

A software transaction is started by the `begin_transaction` statement and completed by the `end_transaction` statement. Our model differs from past research, which uses an `atomic`-block construct, by permitting the beginning and ending of a software transaction to be specified separately. This choice is a direct result of the authors' desire to implement and experiment with the analyses that will be discussed later. That is, the number of benchmarks available today

```
record ColoredShape { int:r, int:g, int:b,
               int:x1, int:y1, int:x2, int:y2,
               int:x3, int:y3, int:x4, int:y4
}
void fun muly(ColoredShape:s, int:amt) {
    s.y1 = s.y1 * amt; s.y2 = s.y2 * amt;
    s.y3 = s.y3 * amt; s.y4 = s.y4 * amt;
}
void fun mulx(ColoredShape:s, int:amt) {
n1: begin_transaction;
    s.x1 = s.x1 * amt; s.x2 = s.x2 * amt;
    s.x3 = s.x3 * amt; s.x4 = s.x4 * amt;
}
int sumx(ColoredShape:s) {
    int tot = s.x1 + s.x2 + s.x3 + s.x4;
    return tot;
}
int fun main() {
    ColoredShape s = ...;    // initialization
n2: thread { begin_transaction; muly(s,3);
n3:          end_transaction; }
n4: thread { mulx(s,0); end_transaction; }
n5: thread { int xtot = sumx(s); ... }
}
```

Fig. 2. Example program. Labels n1-n5 will be used to explain various aspects of the analyses.

that make use of the `atomic`-block construct is currently very small. Therefore, our experiments analyze lock-based programs by treating a lock acquire as a `begin_transaction` and a lock release as an `end_transaction`.[4] In one of the benchmarks discussed in §6.2, the two ends of a matched `begin_transaction` and `end_transaction` pair occur in separate files. Hence, we needed a programming model that could handle the case where a program begins a transaction in one function and ends it in another.

We do expect future programming languages to use the `atomic`-block construct. Because of this, we present two versions for each of our analyses. The first version is for the analysis of programs that use the `atomic`-block construct, while the second is for programs that adhere to the less-structured programming model. Our goal is to allow researchers to perform static analysis of software in a transactional setting. By presenting both versions, we provide algorithms for analyzing software that makes use of an `atomic`-block construct, as well as for

[4] Blundell et al. showed that it is possible to introduce deadlocks when lock-based programs are run/analyzed transactionally by converting lock acquire and lock release into `begin_transaction` and `end_transaction`, respectively [14]. An analysis that detects such situations out of the scope of this paper.

analyzing lock-based programs in a transactional setting. With respect to analyzing lock-based programs, the algorithms we present are useful for both analyzing current lock-based programs for execution on research TM implementations, as well as for analyzing legacy code when TM has become standard.

3 Dynamic Transaction

Here we define the notion of a dynamic transaction. The purpose of this definition is to make clear the distinction between dynamic and static transactions. Dynamic transactions are a runtime notion describing an actual execution of a program, whereas static transactions are intrinsic to the program's text. We present two definitions of a dynamic transaction: (1) for programs that use `atomic` blocks, and (2) for programs that explicity specify the beginning and ending of a software transaction. We refer to the former as *structured* software transactions and the latter as *unstructured* software transactions.

Definition 1. *A dynamic transaction is a sequence of dynamic instructions executed in the scope of an* `atomic` *block.*

Definition 2. *A dynamic transaction is a sequence of dynamic instructions executed between a matched pair of* `begin_transaction` *and* `end_transaction` *instructions.*

4 Static Transaction

A program-analysis tool for understanding transactional software must be able to distinguish between program statements that occur within a dynamic transaction and those that do not. Because a dynamic transaction is a runtime notion, a static-analysis tool cannot work with dynamic transactions directly. For the static analysis of transactional software, we introduce the notion of a *static transaction.* A static transaction is defined in terms of *valid paths* in the program.

Definition 3. *A path in a program's interprocedural control-flow graph (ICFG) is valid if it respects the fact that when a procedure finishes, it returns to the site of the most recent call [15].*

Note that a given valid path may not actually be executable, e.g., due to correlations in the path's branch-conditions.

As we did for dynamic transactions, we present the definition of a static transaction both for (1) programs that make use of structured software transactions, and for (2) programs that make use of unstructured software transactions.

Definition 4. *A static transaction consists of all program statements that lie on a valid path within an* `atomic` *block. A static transaction is represented by the program locations that demarcate the block.*

Definition 5. *A static transaction consists of all program statements that lie on a valid path between a matched pair of* `begin_transaction` *and* `end_transaction` *statements. A static transaction is represented by the pair of program locations for the* `begin_transaction` *and* `end_transaction` *statements.*

A static transaction represents a set of dynamic transactions, namely, those that start at the `begin_transaction` point and end at the `end_transaction` point. Our analyses use sets of static transactions to over-approximate sets of dynamic transactions. We next show, for both structured and unstructured transactions, how the sets of static transactions are determined.

4.1 Structured Software Transactions

It is trivial to determine a program's static transactions when the programming language supports `atomic` blocks. In standard compiler infrastructures, the parser will check for correct syntax of the program and return an abstract syntax tree (AST). The parser can be augmented to record the location of each atomic block in the program. With this information, the node set of a static transaction consists of all program nodes that are within the scope of its `atomic` block and the program nodes of all functions (transitively) called from within that scope.

4.2 Unstructured Software Transactions

To analyze traditional lock-based code in a transactional setting, we treat each lock-acquire and lock-release operation as a `begin_transaction` and `end_transaction`, respectively [16, 17]. This adds considerable difficulty to determining the static transactions of the program—we cannot rely on the parser to verify each software transaction has a matching begin and end. Additionally, we cannot use the reachability relation on the programs's ICFG to determine a programs's static transactions. In this section, we present an interprocedural dataflow analysis to address these problems. Namely, the analysis (1) verifies correct usage of the transactional primitives, and (2) determines the static transactions of a program.

Because converted lock-based programs are allowed to specify the beginning and ending of a software transaction separately, we must take care not to make the detection of static transactions undecidable. The problem is that we are close to having to contend with two interleaved sets of matched parentheses, one (valid paths) for modeling the control flow of the program, and one for modeling the matched `begin_transaction` and `end_transaction` statements. Reps [18] proved that a program-analysis problem that must meet the matching constraints of two interleaved (i.e., shuffled) sets of matched parentheses is undecidable in the general case. To sidestep this undecidability result, we restrict our programming model to allow transactions to be nested to only a finite depth. For the purposes of presenting our analyses, we set the nesting depth to be zero. That is, we will not consider nested transactions in this paper. With a finite nesting depth, we can verify correct usage of the software-transaction primitives using a property automaton [19, 20]. The property automaton for checking correct usage of the `begin_transaction` and `end_transaction` primitives with nesting depth of zero is shown in Fig. 3. It is trivial to expand this automaton to allow for any finite number of nested transactions.

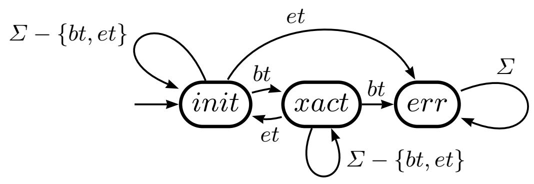


Fig. 3. Property automaton for validating correct transaction usage with a nesting depth of 0. In the diagram, bt represents `begin_transaction`, et represents `end_transaction`, and Σ represents all symbols.

Property automata are useful for answering reachability questions, like incorrect usage of the transactional primitives. This is often done by creating a dataflow-analysis problem in which the automaton's transition relation (often denoted by δ) is used as a state transformer. (More precisely, each transformer is δ restricted to one or more alphabet symbols.) Tab. 1 shows the transformers that model the property automaton from Fig. 3 (for now ignore the bracketed symbols in the subscripts). In Tab. 1, the transformer states model the states of the property automaton. To reduce clutter, transitions to the *err* state are not modeled explicitly; instead, they are modeled by a state q on the left-hand side being disconnected from every state on the right-hand side. This represents an implicit transition from q to the *err* state. In Tab. 1, the top row displays the transformers that correspond to the program statements. Transformer $\delta_{\mathrm{B}[b]}$ corresponds to a `begin_transaction` statement, transformer $\delta_{\mathrm{E}[e]}$ corresponds to an `end_transaction` statement, and transformer δ_{id} corresponds to all other program statements. The second row shows the transformers that can arise through transformer composition.

To verify correct usage of the `begin_transaction` and `end_transaction` primitives, we solve an interprocedural dataflow-analysis problem. We associate dataflow transformers with each edge in the ICFG. To make clear the distinction between dataflow transformers and transformers that model the transition relation of an automaton, we will refer to the latter as δ-transformers, and use the symbol τ for dataflow transformers.

To determine correct usage of the transactional primitives, our dataflow-analysis transformers (τ-transformers) are sets of δ-transformers that model the property automaton. Associated with each edge in the ICFG is a singleton set containing the δ-transformer that encodes the effect of abstractly executing that edge (with respect to the property automaton). Composition of two transformers

τ_1 and τ_2 involves taking the cross product of the two sets of δ-transformers, and performing relational composition on the resulting pairs of δ-transformers. We denote relational composition by ";" (e.g., $\delta_{id}; \delta_{\mathrm{B}[b]} = \delta_{\mathrm{B}[b]}$ and $\delta_{\mathrm{B}[b]}; \delta_{\mathrm{E}[e]} = \delta_{\mathrm{BE}}$).

To solve the dataflow-analysis problem, we use standard techniques [15] to compute a fixpoint. The result of this computation is a set of δ-transformers for each node in the ICFG, where a node's set contains the meet-over-all-paths (MOP) value along valid paths from program entry to that node. To check for correct usage of the transactional primitives, one need only verify that $\tau_{\text{exit}} \subseteq \{\delta_{id}, \delta_{\mathrm{BE}}\}$, where τ_{exit} is the dataflow transformer associated with the exit node of the `main` function.

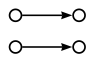
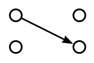
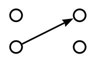
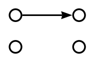
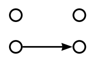
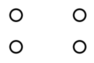
init *xact*			
	(a) δ_{id}	(b) $\delta_{\mathrm{B}[b]}$	(c) $\delta_{\mathrm{E}[e]}$
init *xact*			
	(d) δ_{BE}	(e) $\delta_{\mathrm{EB}[(e,b)]}$	(f) δ_{Err}

Table 1. δ-transformers that encode the transition relation of the property automaton shown in Fig. 3. The left column is a legend labeling the states of the δ-transformers.

$\delta_1; \delta_2$	δ_{id}	$\delta_{\mathrm{B}[b_2]}$	$\delta_{\mathrm{E}[e_2]}$	δ_{BE}	$\delta_{\mathrm{EB}[(e_2,b_2)]}$	δ_{Err}
δ_{id}	δ_{id}	$\delta_{\mathrm{B}[b_2]}$	$\delta_{\mathrm{E}[e_2]}$	δ_{BE}	$\delta_{\mathrm{EB}[(e_2,b_2)]}$	δ_{Err}
$\delta_{\mathrm{B}[b_1]}$	$\delta_{\mathrm{B}[b_1]}$	δ_{Err}	$\delta_{\mathrm{BE}}, (b_1, e_2)$	δ_{Err}	$\delta_{\mathrm{B}[b_2]}, (b_1, e_2)$	δ_{Err}
$\delta_{\mathrm{E}[e_1]}$	$\delta_{\mathrm{E}[e_1]}$	$\delta_{\mathrm{EB}[(e_1,b_2)]}$	δ_{Err}	$\delta_{\mathrm{E}[e_1]}$	δ_{Err}	δ_{Err}
δ_{BE}	δ_{BE}	$\delta_{\mathrm{B}[b_2]}$	δ_{Err}	δ_{BE}	δ_{Err}	δ_{Err}
$\delta_{\mathrm{EB}[(e_1,b_1)]}$	$\delta_{\mathrm{EB}[(e_1,b_1)]}$	δ_{Err}	$\delta_{\mathrm{E}[e_1]}, (b_1, e_2)$	δ_{Err}	$\delta_{\mathrm{EB}[(e_1,b_2)]}, (b_1, e_2)$	δ_{Err}
δ_{Err}	δ_{Err}	δ_{Err}	δ_{Err}	δ_{Err}	δ_{Err}	δ_{Err}

Table 2. Definition of composition of δ-transformers. The labels in square brackets represent the annotation on a δ-transformer. Light grey table entries contain a δ-transformer and a pair, which denotes that the composition also produces a static transaction.

We extend the τ-transformers to collect additional information about the program. Sagiv et al. showed how relations can be annotated with "values" that satisfy certain algebraic properties [21]. Since our dataflow transformers are sets of relations on the states of the property automaton, we use this framework to provide a more general framework for analyzing programs that make use of software transactions (in a manner similar to our programming model). Our first usage of this framework is to determine all of the static transactions of a program.

Let B and E be the set of all `begin_transaction` and `end_transaction` program locations, respectively. We annotate certain δ-transformers with either an element in B or E or a tuple from $E \times B$. Revisiting Tab. 1, the δ-transformers that contain annotations are marked by the bracketed symbols in their subscript. Intuitively, the annotation on a δ-transformer is an "explanation" why that δ-transformer does not contain the edge $init \rightarrow init$. For example, the δ-transformer $\delta_{\mathrm{EB}[(e,b)]}$ in table entry (e) arises from $\delta_{\mathrm{E}[e]}; \delta_{\mathrm{B}[b]}$. It is annotated with (e, b), which records the unmatched `end_transaction` and `begin_transaction` program statements that caused this δ-transformer to arise.

With these annotated δ-transformers, Tab. 2 defines $\delta_1; \delta_2$. Some of the entries in Tab. 2 are highlighted. This is because for those entries, the composition of two annotated δ-transformers also produces an auxiliary tuple (b, e), where $b \in B$ and $e \in E$, which is placed in a global database. These tuples allow us to determine the static transactions of a program.

To use our dataflow transformers in the framework defined in [21], we must show that they adhere to certain algebraic properties. This requires proving that our dataflow transformers form a finite-height meet semi-lattice. Semi-lattice elements are sets of δ-transformers. Let $\varDelta$ be the set of all δ-transformers. The semi-lattice is finite-height because there is only a finite number of δ-transformer sets, i.e., $\mathcal{P}(\varDelta)$. We define the meet operation, $\sqcap$, as set union. Semi-lattice elements are ordered by superset. Because composition of τ-transformers is performed pointwise (i.e., on a per-δ-transformer basis), composition distributes over $\sqcap$; hence, the problem is distributive.

For determining the static transactions of a program, each dataflow transformer is a set of annotated δ-transformers. We associate with each edge in the ICFG the singleton set containing the annotated δ-transformer that corresponds to abstractly executing that edge. Then, using standard techniques [15], the meet-over-all-paths value for each node is found by computing a fixpoint. When the composition of two δ-transformers produces a tuple, we record it in a global database. After the fixpoint has been reached, the database contains all of the program's static transactions. Because we build on the framework that verifies correct usage of the transactional primitives, this analysis also verifies correct usage of the primitives.

Our implementation uses weighted pushdown systems (WPDSs) [22, 23] as the dataflow analysis solver. Reps et al. showed the connection between WPDSs and dataflow analysis [23]. The WPDS algorithms for solving a dataflow-analysis query have the capability to return a *witness trace* [23] for the answer found for each program node. A witness trace can be thought of as a proof for the computed answer. We exploit this capability for alerting the programmer of possible incorrect usage of the `begin_transaction` and `end_transaction` primitives. That is, if after solving the dataflow analysis, $\tau_{\mathrm{exit}} \cap \{\delta_{\mathrm{B}[b]}, \delta_{\mathrm{E}[e]}, \delta_{\mathrm{EB}[(e,b)]}, \delta_{\mathrm{Err}}\} \neq \emptyset$, then there is possible incorrect usage of the primitives. We present to the programmer a path through the program that produces this erroneous result. Due to the abstraction being used, the path may not actually be executable (e.g., due to correlated branches). The programmer can analyze the path and determine if there exists an actual misuse of the primitives in the program.

5 XRef

It is useful for a programmer to know what record fields are accessed in the dynamic transactions during program execution. This is important both for program understanding and debugging. For example, when adding fields to a record type or splitting a large record type into two, the programmer must be aware of the fact that the fields of an instance of that record are guarded by a software transaction. We are able to present to the programmer an approximation of this information through XRef analysis. XRef analysis approximates the set of fields accessed in dynamic transactions by annotating the fields of each record type with the static transactions in which they are referenced. XRef analysis can be viewed as inferring annotated types, where the annotations are the static transactions in which each field of a record type is referenced.

5.1 Structured Software Transactions

When the program being analyzed makes use of the `atomic`-block construct, XRef analysis can be performed by a flow-insensitive interprocedural analysis (similar to GMOD/GUSE analysis [24]). Because of the similiarities between XRef analysis (for the `atomic`-block construct) and GMOD/GUSE analysis, we only sketch the algorithm.

Let R be the set of all record-type names, and F be the set of all field names. For each static transaction, the algorithm computes a set of (fully-qualified) field accesses s, where each field accesses is of the form $r.f$ with $r \in R$ and $f \in F$. For each function of the program, perform an intraprocedural analysis that determines all field accesses performed by that function. The accesses are represented by a set s. This can be accomplished with a single pass over each program node in a function's control-flow graph (similar to IUSE analysis). Once this information has been computed, next perform a fixpoint calculation over the callgraph to determine the field accesses made transitively by each function (similar to GUSE analysis). Finally, for each function that contains an `atomic` block, traverse the program statements that are in the scope of the `atomic` block, unioning the accesses for each program statement. If a program statement is a function call, the set of accesses is retrieved from the sets that were calculated from the fixpoint computation on the callgraph. Once this information has been computed for each static transaction, the fields of each record type are annotated with the static transaction(s) in which it is accessed.

5.2 Unstructured Software Transactions

We make use of the framework presented in §4.2 to analyze lock-based programs converted to use `begin_transaction` and `end_transaction`. To do this, we add to each δ-transformer's annotation a set of field accesses, as defined in §5.1. Specifically, for each δ-transformer in the top row of Tab. 1, we add to the annotation a set s, which is shown in Tab. 3. We make a few changes to the composition of δ-transformers. For brevity, we enumerate the changes here instead of replicating Tab. 2. We use the notation (s, δ) to represent an annotated δ-transformer extended with the set of field accesses s. Likewise, we use the notation $(s_1, \delta_{\mathrm{EB}[(e,b)]}, s_2)$ to represent that $\delta_{\mathrm{EB}[(e,b)]}$ has two sets, s_1 and s_2, where s_1 is the set of fields accessed in a static transaction ending at e and s_2 is the set of fields accessed in a static transaction beginning at b. We define ";" as follows (see below for an explanation):

1. $(s_1, \delta_{\mathrm{B}[b]}); (s_2, \delta_{\mathrm{E}[e]}) = (\emptyset, \delta_{\mathrm{BE}}), (b, e, s_1 \cup s_2)$
2. $(s_1, \delta_{id}); (s_2, \delta_{\mathrm{B}[b]}) = (s_2, \delta_{\mathrm{B}[b]})$
3. $(s_1, \delta_{\mathrm{BE}}); (s_2, \delta_{\mathrm{B}[b]}) = (s_2, \delta_{\mathrm{B}[b]})$
4. $(s_1, \delta_{\mathrm{E}[e]}); (s_2, \delta_{\mathrm{B}[b]}) = (s_1, \delta_{\mathrm{EB}[(e,b)]}, s_2)$
5. $(s_1, \delta_{\mathrm{E}[e]}); (s_2, \delta_{id}) = (s_1, \delta_{\mathrm{E}[e]})$
6. $(s_1, \delta_{\mathrm{E}[e]}); (s_2, \delta_{\mathrm{BE}}) = (s_1, \delta_{\mathrm{E}[e]})$
7. $(s_1, \delta_{id}); (s_2, \delta_{\mathrm{EB}[(e_1,b_1)]}, s_3) = (s_1 \cup s_2, \delta_{\mathrm{EB}[(e_1,b_1]}, s_3)$
8. $(s_1, \delta_{\mathrm{EB}[(e_1,b_1)]}, s_2); (s_3, \delta_{id}) = (s_1, \delta_{\mathrm{EB}[(e_1,b_1]}, s_2 \cup s_3)$
9. $(s_1, \delta_{\mathrm{B}[b_1]}); (s_2, \delta_{\mathrm{EB}[(e_2,b_2)]}, s_3) = (s_3, \delta_{\mathrm{B}[b_2]}), (b_1, e_2, s_1 \cup s_2)$
10. $(s_1, \delta_{\mathrm{EB}[(e_1,b_1)]}, s_2); (s_3, \delta_{\mathrm{E}[e_2]}) = (s_1, \delta_{\mathrm{E}[e_1]}), (b_1, e_2, s_2 \cup s_3)$
11. $(s_1, \delta_{\mathrm{EB}[(e_1,b_1)]}, s_2); (s_3, \delta_{\mathrm{EB}[(e_2,b_2)]}, s_4) = (s_1, \delta_{\mathrm{EB}[(e_1,b_2]}, s_4), (b_1, e_2, s_2 \cup s_3)$
12. otherwise $(s_1, \delta_1); (s_2, \delta_2) = (s_1 \cup s_2, (\delta_1; \delta_2))$

Let us now explain this definition by means of a few examples. Intuitively, we want to only record field accesses that occur within a static transaction. This is exemplified by rule 2. The composition $(s_1, \delta_{id}); (s_2, \delta_{\mathrm{B}[b]})$ results in $(s_2, \delta_{\mathrm{B}[b]})$. This has the effect that the composition ignores all field accesses that occur *before* the `begin_transaction` statement. Similiarly, rules 3–6 ignore all field accesses that occur *after* an `end_transaction` statement. Notice that the cases specified in rules 1 and 9–11 each produce an auxiliary triple. This is because those rules result from the matching of a `begin_transaction` and `end_transaction` statement. Specifically, for rule 10, the composition of $(s_1, \delta_{\mathrm{EB}[(e_1,b_1)]}, s_2); (s_3, \delta_{\mathrm{E}[e_2]})$ results in the annotated δ-transformer $(s_1, \delta_{\mathrm{E}[e_1]})$ along with the auxiliary triple $(b_1, e_2, s_2 \cup s_3)$. The triple denotes that static transaction (b_1, e_2) accessed the fields contained in the set $s_2 \cup s_3$. When an auxiliary triple is produced, we record this information in a global database.

Each node of the ICFG is annotated with its corresponding dataflow transformer as in §4.2. As before, we use standard techniques to compute the MOP dataflow transformer for each program node in the ICFG. Once the dataflow analysis has completed, the global database contains triples of the form (b, e, s), such that $b \in B$, $e \in E$, and s is a set of field accesses. We use this information

Program Statement	**δ-transformer**	**Pair Set**
n1: `begin_transaction`	$\delta_{\mathrm{B}[n1]}$	$\emptyset$
n1: `end_transaction`	$\delta_{\mathrm{E}[n1]}$	$\emptyset$
n1: $x = r_1.f_1$	δ_{id}	$\{(r_1.f_1)\}$
n1: $r_1.f_1 = x$	δ_{id}	$\{(r_1.f_1)\}$

Table 3. Example program statements; their corresponding δ-transformers; and the set of field accesses that annotates them.

to annotate the fields of each record type with the static transactions in which it is accessed.

When interpreting the results our experiments, we found XRef analysis to be extremely helpful. Analyzing the information obtained from XRef analysis led us to realize that dynamic transactions were aborting because of false conflicts. We address this issue with our next analysis, XOrder.

6 XOrder

XOrder is an analysis that determines an improved layout for the fields of a record type. It identifies these reorderings by analyzing the results of XRef analysis. The experiments reported in §6.2, show that, without programmer intervention, XOrder can reduce the rate of false conflicts for programs running on a transactional memory system.

Definition 6. *A false conflict occurs when two distinct dynamic transactions access separate bytes of memory, but, due to the conflict-detection scheme of the transactional memory system, one of them is forced to stall or abort.*

Although false conflicts can occur in both STMs and HTMs, they are especially prevelent in HTMs that detect conflicts using the coherence mechanism. For clarity, in this section, we assume an HTM.

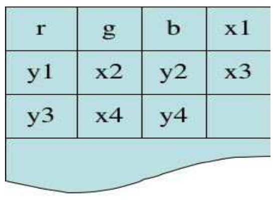


Fig. 4. Possible layout in memory of the shared record `s` from Fig. 2. Each row represents one cache line of memory.

In our target HTM implementation, the granularity of precision is one cache line. Therefore, during a dynamic transaction, the HTM's conflict-detection mechanism does not distinguish between memory reads and writes to the same cache line. Fig. 4 depicts a possible layout in memory of the shared `ColoredShape` record `s` from the program in Fig. 2. Assuming that integers occupy four bytes of memory and that the cache-line size is sixteen bytes, accesses to any of the fields {`r, g, b, x1`} are not differentiated by the HTM's conflict-detection mechanism. That is, an access to any of the fields will mark the *entire* cache line as accessed due to the HTM's conflict-detection granularity. Similarly, accesses to any of {`y1, x2, y2, x3`} will not be distinguished and accesses to any of {`y3, x4, y4`} will not be distinguished. This memory alignment, combined with the HTM's conflict-detection mechanism, will cause a false conflict between the concurrent execution of transactions (`n2`,`n3`) and (`n1`,`n4`) from the program in Fig. 2. It is a false conflict because the two transactions do not access any common fields of the shared `ColoredShape` record `s`. To tackle this problem, we developed an analysis algorithm, XOrder, that determines an optimized layout ordering for record types.

Record-layout reordering is a technique that analyzes which fields of a particular record type might be accessed in a dynanic transaction. The result of XRef is the set of fields of record types accessed in a static transaction. Thus, XRef computes a superset of the fields actually accessed in a dynamic transaction. The idea behind record-layout reordering is that if two fields, f_1 and f_2, are accessed only in separate dynamic transactions, then the layout of the record type in memory should be chosen to ensure that these fields reside in separate cache lines. Because we are performing static analysis, we do not know where in memory a record instance will be dynamically created, and furthermore we do not know its alignment with respect to cache lines. Therefore, our goals are: (1) to separate f_1 and f_2 with fields that are not accessed in a static transaction, and (2) to ensure that the sum of the sizes of these "padding" fields is greater than or equal to the size of a cache line. A beneficial byproduct of this ordering is that the number of cache lines accessed by a dynamic transaction is potentially decreased. This is akin to the *cache-block working set* optimization described by Chilimbi et al. [25].

XOrder uses the field annotations inferred by XRef to determine an optimized ordering of a record type's fields. With respect to [25], we do not use dynamic profiling information to determine a field ordering. Instead, we rely on the field accesses that occur in a static transaction.

Intuitively, the ordering determined by XOrder should be such that each static transaction accesses a contiguous region of memory. When the fields accessed by a static transaction do not overlap with the fields accessed by any other static transaction, determining this ordering is trivial. We create an undirected graph, where the nodes of the graph correspond to the fields of the record type. There is an edge between two nodes (fields) if they are accessed in the same static transaction. In Fig. 5, the `x` fields are all connected because they are accessed in the static transaction (`n1`,`n4`) and the `y` fields are all connected because they are accessed in the static transaction (`n2`,`n3`). When ordering these fields, each connected component represents nodes that should be laid out near each other. A (linearization of a) spanning tree for the connected component gives a linear order for those fields.

In some cases, the accesses of two static transactions will share some subset of a record type's fields. We refer to these static transactions as a transactional group.

Definition 7. *A transactional group consists of 2 or more static transactions such that there is a common field shared between at least two of the static transactions in the group.*

In these situations, the fields of a transactional group are ordered such that each static transaction of the group accesses contiguous regions of memory. One solution to find such an ordering (if it exists) is to solve an instance of the traveling-salesman problem (TSP). Create a graph where the nodes of the graph represent the fields of the transactional group. For each pair of nodes, add a weighted edge to the graph. The weight of the edge is determined by the static transactions of the group. That is, if the two fields represented by the nodes are accessed in the same static transaction, then the weight is 1. Otherwise, we set the weight to be greater than 1. By setting the weight to be greater than 1, a solution to the TSP will not traverse that edge unless it is absolutely necessary. In our experiments, we used the weight 10. For such graphs, an optimal solution to the TSP will produce the desired ordering. The path can be used to create the record layout. If it is possible for every static transaction of the group to access contiguous memory, then this ordering will provide it. In cases where no such ordering exists, the ordering produced by solving the generated instance of the TSP will provide a good approximation.

Because we are targeting our analysis for a compiler infrastructure, solving an NP-complete problem like the TSP every time the program is modified might be too costly. Therefore, we use the well-known heuristic of using a minimum-spanning-tree (MST) algorithm to approximate the TSP [26]. Approximating the TSP solution using an MST is nice because it still takes the graph's edge weights into account. For example, one could imagine using dynamic-profiling information to adjust the weights on the graph, effectively biasing the solution to the TSP to prefer certain paths (orderings) over others. This would allow XOrder to perform an optimization akin to the *field-layout-affinity* method proposed by Chilimbi et al. [25]. Because we use an MST to approximate a solution to the TSP, we no longer need to distinguish between transactional groups and static transactions (that are not members of a group). This is because we can use a linearization of the MST to compute an ordering for both cases.

Once the layout of each static transaction and transactional group is determined, we next use the record type's fields *not* accessed in a static transaction as padding between these orderings. If there are n ordered sets, then XOrder attempts to find $n - 1$ sets of padding fields such that the size of each set is at least the size of the cache line for the target architecture. To do this, we sort the padding fields in decreasing order by their size and then (attempt to) greedily fill the $n - 1$ sets. Fig. 6 displays the layout of `ColoredShape` after analyzing the program in Fig. 2 with XOrder. Notice that the analysis suggested

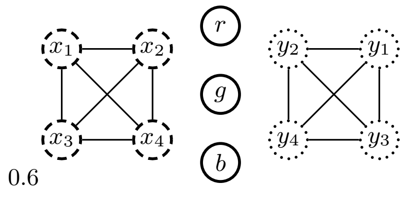


Fig. 5. The graph generated during XOrder analysis for the program in Fig. 2.

the insertion of an integer field named `pad1`. This is because for the example program (and target architecture with a cache-line size of 16 bytes), there are not enough fields to place between the two static transactions. Our analysis only suggests the padding in a comment instead of directly emitting it because the addition of extra fields can impact the performance of a program. For example, if the program allocated a million `ColoredShape` objects, then the addition of the padding field would cause 4 MB of memory to be wasted. Additionally, adding pad fields will affect the runtime behavior of the program because it places extra pressure on the cache. Because of the padding suggestions, we do not directly modify the analyzed program. Instead, we emit the reorderings for each record type to the programmer. The programmer can then decide whether to apply the reordering.

```
record ColoredShape {
    int:x1, int:x2, int:x3, int:x4,
    int:r, int:g, int:b,/*int:pad1,*/
    int:y1, int:y2,int:y3, int:y4
}
```

Fig. 6. A reordering of the fields of ColoredShape suggested by XOrder.

6.1 Discussion

XOrder analysis is a whole-program analysis. Field reordering can break programs that make use of shared libraries that are compiled assuming a certain field layout. In addition to this, some programs write data to a persistent store. Reordering of fields can cause an incompatibility with the data in the persistent store. However, if the benefits from field reordering are large enough, we imagine that the programming effort required to make use of these fields is justifiable.

6.2 XOrder Experiments

We evaluated XOrder on three programs from the SPLASH-2 benchmark suite [27], modified to use transactions in place of locks [10]. The SPLASH-2 programs

Benchmark	# Procs	Δ-Aborts	Relative Speedup
raytrace	2	-32.7	1.00
	4	-26.0	1.02
	8	-11.5	1.08
	16	41.0	1.25
	32	-65.5	2.78
mp3d	2	0	1.00
	4	390	0.98
	8	-682	0.96
	16	12600	0.85
	32	2640	1.00
radiosity	2	-6.50	0.99
	4	-8.75	1.00
	8	-450	1.01
	16	-6500	1.37
	32	2810	0.82

Table 4. Experimental results for running the raytrace, mp3d, and radiosity benchmarks from the Splash2 benchmark suite. *Δ*-Aborts reports the difference in the number of aborts between reordered benchmarks and the original. The smaller the value the better. The right column measures (relative) speedup of the reordered benchmark over the original. The larger the value the better.

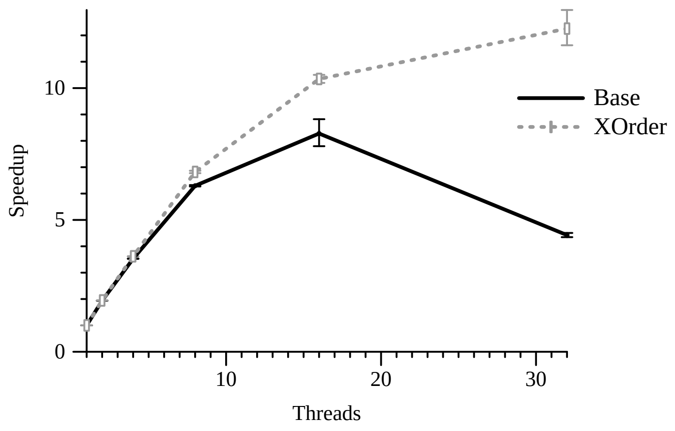


Fig. 7. Overall speedup comparison for the raytrace benchmark. Base and XOrder show the speedup before and after optimizing the program with the results of XOrder analysis.

are written in `C`.[5] We modeled a 32-processor SPARC multiprocessor running

[5] The `C` programming language is neither typesafe nor memory safe. Because of this, both XRef and XOrder are unsound. The application of XRef and XOrder analyses to a type and memory safe language would be sound.

Solaris 9 with support for HTM using the Simics full-system simulator [28] extended with a detailed memory system timing model from the GEMS [29, 30] toolkit. Our simulated system includes 32, 1-GHz SPARC processors, each with 4 MB of private cache. The system includes HTM support based on LogTM [10], which performs conflict detection at the cache-line granularity. For our experiments, we used a cache line size of 64 bytes.

We compare the performance of the programs in their original form and the programs modified to use the orderings suggested by XOrder. For each of our benchmarks, we ran both versions of the program on our simulated machine with a range of thread counts. Tab. 4 displays the effect of the reordering on the overall runtime of the benchmarks and on the frequency of transaction aborts, a major contributor to the execution time.

Not surprisingly, our results vary for each benchmark. For Raytrace, despite having little effect on the number of aborts, the reordering provided by XOrder results in a dramatic improvement in relative performance (a factor of 2.8 for 32 threads, yielding an overall speedup of 12). This result matches Moore et al.'s [10] observation that Raytrace suffers from false conflicts. The performance improvement is primarily due to the improved scalability of the benchmark. As shown in Fig. 7, eliminating the false conflicts between transactions allows the reordered Raytrace to continue to scale to 32 threads, while the original program performance degrades after 16.

On Radiosity, XOrder at first appeared to provide an improvement. The number of aborts steadily decreased up to 16 processors. However, the number of aborts increased and performance worsened for 32 processors. We are currently modifying the simulator to track additional processor state, e.g, we are not able to separately measure true and false conflicts at this time. This will help shed light on the cause of the performance loss.

For MP3D, on 16 processors, the layout XOrder suggested caused an increase in the number of aborts, which degraded performance for 16 threads. For 32 threads, despite a small increase in aborts, performance is unaffected.

Although our measured results show improvement in only one of our test cases, we believe XOrder can still be a help to programmers. XOrder revealed the performance bug in Raytrace immediately. For MP3D, it was already tuned to avoid false sharing. Our future work includes analyzing more benchmarks and further investigating the behavior of Radiosity. Hopefully, the investigations can help us improve XOrder's field-layout algorithm.

7 XProtect

Software transactions are arguably superior to traditional locks; however, they do not eliminate all programming errors due to concurrency. For example, when used incorrectly, programs that inconsistenly use software transactions can produce erroneous results. In the program shown in Fig. 2, the value returned from the call to `sumx` can have five possibilities instead of two. This is due to the non-determinism of the thread scheduler. Specifically, it depends on how the thread that is started at location `n4`, t_{n4}, is interleaved with the thread started at location `n5`, t_{n5}. If t_{n4} commits before t_{n5} begins, then the result will be 0. If t_{n4} commits after t_{n5} has read `s.x1`, the result will be `s.x1`. This pattern continues up to the case where t_{n4} commits after t_{n5} has read all of the `x` fields. Had the programmer protected the call to `sumx` with a transaction, there would be only two possible results, namely, (i) 0 in the case that t_{n4} commits before t_{n5}, and (ii) the sum of the values of all the `x` fields otherwise.

The underlying problem is that the call to `sumx` is not protected by a software transaction. In the terms of Flanagan and Qadeer, the function `sumx` does not have the `atomicity` property [31]: "if a method is atomic, then any interaction between that method and steps of other threads is guaranteed to be benign".

We use XProtect analysis to address this problem. XProtect analysis is a heuristic to check for atomicity violations. Similiar to the work in [32], XProtect checks that accesses to a shared-record instance are consistently protected by a software transaction. Consistency checking does not guarantee the atomicity property (e.g., guarding each individual program statement with a software transaction produces a consistent program); however, an inconsistent program is likely to violate the atomicity property.

The idea behind consistency checking is to infer a correctness specification from the program's code. That is, the *safety property* that XProtect attempts to verify is that all accesses to a shared-record instance are proteted by a software transaction. The correctness specification inferred by XProtect is the set of record-instances that are shared. It does this by determining which record-instances are protected by a software transaction *at some point* during program execution.

XProtect is an extension of XRef analysis. It can be viewed as further refining the type annotations inferred by XRef analysis for the fields of each record type. The refinement consists of adding the results from a sound pointer analysis to the annotations. We chose Steensgaard's analysis [33] because it is sound for concurrent programs: a flow-insensitive analysis considers all interleavings of the various threads that make up the concurrent program. Other more expensive pointer analyses that are still sound for concurrent programs would work just as well.

As before, we describe XProtect analysis for programs that make use of the `atomic`-block construct and those that specify the beginning and ending of a software transaction separately. In both cases, we compute the results from two dataflow-analaysis problems, and the answer we are interested in is computed from the differences in the values computed by the two analysis phases.

7.1 Structured Software Transactions

For programs that make use of the `atomic`-block construct, XProtect is a straightforward extension of XRef. The key is to extend the sets of field accesses to include both the abstract record-allocation site[6] that is accessed, as

[6] We use the term "abstract record-allocation site" to mean the set of record-allocation sites obtained after pointer analysis has finished.

well as an indication of what type of memory-access is made, i.e., either a read or a write. XProtect differentiates between reads and writes so that it does not produce a warning when shared memory is only read and never written.

Specifically, we modify the XRef algorithm to compute, for each static transaction, a set of tuples of the form $(R.F, A, T)$, where R and F are as in XRef, A is the set of abstract record-allocation sites, and $T \in \{read, write\}$. We label each node of the program with a set of tuples s that corresponds to that node's accesses, and the manner in which they are made. For example, a program node that represents the program statement $x = r_1.f_1$ is labeled with the tuple set $\{(r_1.f_1, a, read) \mid a \in A_{r_1}\}$, where A_{r_1} is the set of abstract record-allocation sites that are accessed. Using the extended sets of tuples, the algorithm for solving XRef (defined in §5.1) computes, for each abstract record-allocation site, the set of fields either read or written by each static transaction. We denote this set by s_{xact}.

To verify that the field accesses to all shared record instances are consistently protected by a software transaction, we solve a second dataflow-analysis problem, which determines all field accesses that occur outside every static transaction. A second dataflow-analysis problem is required because a function may be called both from within a transaction and outside of one. Therefore, it is possible for that function to make accesses to the same shared record instance in a transactional and nontransactional context.

We collect all nontransactional accesses via a simple trick. We treat each `atomic` block as a "`noop`" instruction. That is, the analysis ignores the statements in the body of each atomic block. For each function, we compute the set of field accesses to the abstract record-allocation sites by visiting each node in the function's control flow graph (CFG) and taking the union of their accesses. Next, we solve a set of equations on the program's call-graph to compute the set of abstract record-allocation site field accesses made (transitively) by each function. All nontransactional field accesses to abstract record-allocation sites are precisely the label on the `main` function in the call-graph. We denote this set by s_{access}.

Once s_{access} has been computed, we check to see whether a field is accessed both transactionally and nontransactionally, with one of the accesses being a write. For each read access in s_{xact}, we check to see whether s_{access} contains a write access to the same field. For example, if $(r_1.f_1, a, read) \in s_{\text{xact}}$, which denotes a read of the f_1 field of record type r_1 for abstract record-allocation site $a \in A$, we check whether $(r_1.f_1, a, write) \in s_{\text{access}}$. Similarly, for each write access in s_{xact}, we check whether there is a corresponding read or write access to the same field in s_{access}. If either of these checks succeed, then we warn the programmer that there is a potential data race. The warning includes the field and abstract record-allocation site that is inconsistently guarded by a software transaction.

7.2 Unstructured Software Transactions

To perform XProtect analysis on programs that specify the beginning and ending of software transactions separately, we extend the XRef analysis presented in §5.2. The sets of field accesses used in XRef analysis are extended to be sets of tuples. Each tuple is of the form $(R.F, A, T)$, where R is the set of all record type names, F is the set of all record-type fields, A is the set of abstract record-allocation sites, and $T \in \{read, write\}$. With respect to XRef analysis, the extensions have no additional effect when δ-transformers are composed. We note that we have only increased the size of the annotations by a finite amount, compared to XRef analysis. Moreover, all algebraic properties that were shown to hold earlier are still valid.

As in XRef analysis, we label each edge of the ICFG with its corresponding set of annotated δ-transformers. We then solve the dataflow-analysis problem as before, which populates the global database with the set of fields accessed in a static transaction for each abstract record-allocation site. We denote the set of abstract record-allocation site fields accessed in some static transaction by s_{xact}.

To determine the field accesses made to abstract record-allocation sites while not in a static transaction, we to run XProtect again; however, for this second run we modify the definition of ";". The key is to realize that the information sought is the *opposite* of the information computed by XProtect. We compute these unprotected accesses by "inverting" the operations on the annotations of the δ-transformers when composing δ-transformers. Intuitively, we modify the definition of ";" to be such that it only records accesses that occur *outside* of a static transaction. This can be accomplished by making the following changes to ";" (we use the same notation as in §5.2). For instance, in rule (1) below, the tuples in s_2 are dropped because they represent accesses that occur inside of a static transaction.

1. $(s_1, \delta_{\text{B}[b]}); (s_2, \delta_{id}) = (s_1, \delta_{\text{B}[b]})$
2. $(s_1, \delta_{id}); (s_2, \delta_{\text{E}[e]}) = (s_2, \delta_{\text{E}[e]})$
3. $(s_1, \delta_{id}); (s_2, \delta_{\text{EB}[(e_1,b_1)]}, s_3) = (s_2, \delta_{\text{EB}[(e_1,b_1)]}, s_3)$
4. $(s_1, \delta_{\text{EB}[(e_1,b_1)]}, s_2); (s_3, \delta_{id}) = (s_1, \delta_{\text{EB}[(e_1,b_1)]}, s_2)$
5. $(s_1, \delta_{\text{E}[e]}); (s_2, \delta_{\text{B}[b]}) = (s_1 \cup s_2, \delta_{\text{EB}[(e,b)]}, \emptyset)$
6. $(s_1, \delta_{\text{B}[b_1]}); (s_2, \delta_{\text{EB}[(e_2,b_2)]}, s_3) = (s_1 \cup s_2 \cup s_3, \delta_{\text{B}[b_2]})$
7. $(s_1, \delta_{\text{EB}[(e_1,b_1)]}, s_2); (s_3, \delta_{\text{E}[e_2]}) = (s_1 \cup s_2 \cup s_3, \delta_{\text{E}[e_1]})$
8. $(s_1, \delta_{\text{EB}[(e_1,b_1)]}, s_2); (s_3, \delta_{\text{EB}[(e_2,b_2)]}, s_4) =$
   $(s_1 \cup s_2 \cup s_3 \cup s_4, \delta_{\text{EB}[(e_1,b_2]}, \emptyset)$
9. otherwise $(s_1, \delta_1); (s_2, \delta_2) = (s_1 \cup s_2, \delta_1; \delta_2)$

Using this modified composition of δ-transformers, we perform a second fixpoint calculation. All non-transactional field accesses (i.e., s_{access}) are the annotations associated with δ_{id} and δ_{BE} in the dataflow transformer on the `main` function's exit node.

Finally, we perform the check with respect to s_{xact} and s_{access} described in §7.1 to see if there are potential inconsistencies with respect to the use of static transactions when accessing the fields of a shared record. If an inconsistency exists, we report it to the programmer.

Again, because we use WPDSs as our dataflow-analysis solver, we take advantage of their witness-tracing capabilities. (A witness trace is a "proof" for a computed dataflow value and encodes the set of program paths that gave rise to it, along with their intermediate dataflow values.) We extract from the witness trace a path that accesses a field of the shared record while not in a static transaction. We present to the programmer this path as well as a static transaction that accesses the same field in a conflicting manner, e.g., a read and a write.

7.3 XProtect Discussion

For the example program in Fig. 2, XProtect emits twelve warnings. Eight of these are benign consistency violations. This is due to the fact that the program initializes the `x` and `y` fields of the shared `ColoredShape` record `s` before starting any threads. Adopting the policy of tools such as Eraser [34], which make a special case for the initialization of global variables, could eliminate these cases.

The other four warnings have more severe consequences. The problem is because the reads of the `x` fields from t_{n5}'s call to `sumx` execute concurrently with the writes to the `x` fields from t_{n4}'s call to `mulx`. As explained earlier, this causes the program to have more behaviors than the programmer intended. XProtect alerts the programmer of these inconsistency violations. In doing so, XProtect implicitly notifies the programmer that the call to `sumx` was not guarded with a software transaction.

We note that due to the imprecision of pointer analysis and the abstract model of the program that we analyze (i.e., we do not interpret conditions), a warning does not guarantee that there exists an inconsistency. Additionally, XProtect emits warnings for benign inconsistencies. However, we believe that XProtect is a useful analysis to aid programmers in reasoning about their software. Proving that a program consistently protects shared data with a software transaction takes a step toward verifying correctness. That is, XProtect can be used as an inexpensive analysis that alerts the programmer of inconsistencies. If inconsistencies exist, the programmer can then apply other more heavy-weight analyses.

8 Related Work

The use of transformers for performing interprocedural-dataflow analysis was introduced by Cousot and Cousot [35] and Sharir and Pnueli [15]. Sagiv et al. showed how this framework, where the transformers are relations annotated with "values" that exhibit certain algebraic properties, can be used to precisely solve instances of copy propagation, namely copy-constant propataion and linear-constant propagation [21]. We used this framework for analyzing programs that adhere to our programming model.

Abstract interpretation was defined in the seminal work by Cousot and Cousot [36]. The analyses that we present can be viewed as an abstract interpretation of the program, where the abstract semantics of a program statement is its effect on the property automaton that checks a policy for correct usage of the transactional primitives.

XOrder analysis is a program optimization whose goal is to reduce false conflicts of a transactional program executing on a hardware ISA that supports transactional memory. The HTM implementation we target performs conflict detection through the cache-coherence protocol [10]. Chilimbi, Davidson, and Larus also used record-layout reordering as an optimization to improve a program's effective use of hardware caches [25]. Their analyses incorporated profile information obtained from runs of the program. Our optimization, XOrder, is a purely static analysis. In contrast to the work by Chilimbi et al., we reorder a record type's layout according to its accesses in static transactions. It is left to future work to determine if incorporating dynamic profiling information into XOrder's record layout algorithm could improve our optimization.

Recent work by Harris et al. [37] and Adl-Tabatabai et al. [38] was concerned with optimizing a program's use of software transactional memory (STM). Their work is based on the observation that, by breaking down the inserted calls to the STM's runtime system, standard compiler optimizations, such as dead-code elimination and common subexpression elimination, can be used to optimize a program with respect to the number of calls it makes to the STM's runtime system. XOrder analysis is also concerned with optimizing a program that runs on a system that supports transactional memory. In our case, we optimize the program itself (i.e., the layout of the record types), and not the inserted program statements. It would be interesting to see if our techniques would result in additional performance gains in these other systems.

Flanagan and Qadeer proposed that program methods should exhibit the atomicity property [31]. Their work made use of a type system to ensure this property. XProtect detects inconsistency violations in a program. We view this as a heuristic that searches for the manifestation of a function not exhibiting the atomicity property. The Locksmith tool [32] detects data races by finding occurrences where shared data is not consistently protected by the same lock. XProtect is similiar to this work because they both involve consistency checking; however, XProtect detects consistencies with respect to software transactions.

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