Composing Relaxed Transactions

Vincent Gramoli
University of Sydney
Email: vincent.gramoli@epfl.ch

Rachid Guerraoui
EPFL
Email: rachid.guerraoui@epfl.ch

Mihai Letia
EPFL
Email: mihai.letia@epfl.ch

***Abstract*—As the classical transactional abstraction is sometimes considered too restrictive in leveraging parallelism, a lot of work has been devoted to devising relaxed transactional models with the goal of improving concurrency. Nevertheless, the quest for improving concurrency has somehow led to neglect one of the most appealing aspects of transactions: software composition, namely, the ability to develop pieces of software independently and compose them into applications that behave correctly in the face of concurrency. Indeed, a closer look at relaxed transactional models reveals that they do jeopardize composition, raising the fundamental question whether it is at all possible to devise such models while preserving composition. This paper shows that the answer is positive.**

We present outheritance, a necessary and sufficient condition for a (potentially relaxed) transactional memory to support composition. Basically, outheritance requires child transactions to pass their conflict information to their parent transaction, which in turn maintains this information until commit time. Concrete instantiations of this idea have been used before, classical transactions being the most prevalent example, but we believe to be the first to capture this as a general principle as well as to prove that it is, strictly speaking, equivalent to ensuring composition.

We illustrate the benefits of outheritance using elastic transactions and show how they can satisfy outheritance and provide composition without hampering concurrency. We leverage this to present a new (transactional) Java package, a composable alternative to the concurrency package of the JDK, and evaluate efficiency through an implementation that speeds up state of the art software transactional memory implementations (TL2, LSA, SwissTM) by almost a factor of 3.

***Index Terms*—composition; relaxed transactions; reusability**

I. Introduction

One of the most desirable properties in software engineering is *composition*. Basically, pieces of software, called *components*, should be developed and tested independently and then later composed to create larger software pieces and ultimately applications. Szyperski [1] argues that, like in all other engineering disciplines, designing software for composition is crucial, naming reuse, time to market, quality and viability as some of the key benefits.

Composition in the sequential domain has been studied extensively and techniques such as object oriented programming have proved to be very useful in this regard. However, recent technological trends have introduced concurrency into programming, rendering composition significantly more challenging. Key properties such as *atomicity* and *deadlock freedom* are hard to preserve under composition. Other great works [2], [3] consider *parallel composition* of software. In this view, two operations π_1 and π_2 are said to be composed when they are executed in parallel by different processes. In this paper, we consider *concurrent composition*, meaning that operations π_1 and π_2 are invoked in sequence by a higher level operation π (referred to as a composed operation), and that multiple instances of π can be executed in parallel.

The following simple example from Harris et al. [4] illustrates the difficulty of composing lock-based programs: remove and put cannot be composed into a move operation because a concurrent execution with two instances of move, one moving a value from key k to k' and another one from key k' to k would be deadlock-prone. In the same vein, lock-free implementations are generally hard to compose. It is for instance impossible to use the remove and put operations of a hash table to obtain a concurrent move operation that can be used to rebalance the table after a resize [5]. Indeed, the difficulty of composing lock-free operations is a major limitation of the java.util.concurrent package [6] of the JDK [7]–[9]. For example, the size method of the ConcurrentSkipListMap class is known not to be atomic, forcing the user to explicitly lock existing sequential data structures in a coarse-grained manner, which then severely hampers concurrency.

A memory *transaction* is an appealing concurrent programming abstraction for it makes programs easily composable [4], [10]–[12]. Composing with transactions simply consists of encapsulating operations inside a new transaction [4], without needing to modify the code as when using techniques based on compare-and-swap [13]. The result is a composition that preserves atomicity and deadlock-freedom. One can furthermore use transactions to compose operations that are themselves obtained through composition, and so on. This modular development process has the potential to greatly simplify the task of the programmer.

Yet, transactions in their classical form are often considered too restrictive [14]. They tend to reduce concurrency by over-conservatively aborting transactions even in executions that would semantically be correct at the application level, should the transactions be actually committed. Several variants of the original transactional abstraction have been proposed, all pro-

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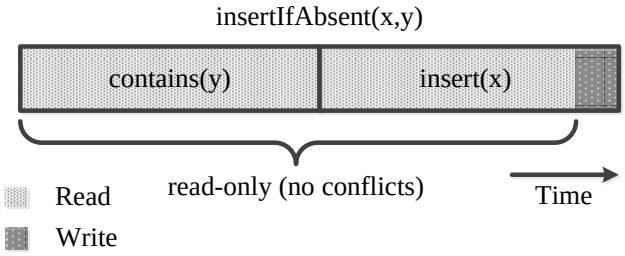


Fig. 1. Composing an insertIfAbsent.

moting concurrency by accounting for application semantics when orchestrating transaction interleaving [15]–[20]. These are referred to as *relaxed* (or *weak*) models because they allow more interleavings with the intent of providing better performance. Typically, these models do not blindly reason at the level of memory reads and writes when detecting conflicts between concurrent transactional operations, but rather require from the programmer to somehow encode the way higher-level operations conflict. Relaxed transactions [21] have been shown to significantly outperform classical transactions using realistic workloads such as the STAMP benchmark suite [22].

However, the attention has mainly been devoted to efficiently implementing these models, forgetting sometimes about one of the most appealing aspects of transactions, namely *composition*. In fact, a closer look reveals that composition can sometimes easily be compromised when relaxing the original transactional model. We illustrate this using the elastic model [17], designed to take advantage of the semantics of search data structures. Elastic transactions improve concurrency by ignoring conflicts generated by their read-only prefix, as in the case of lists, trees, etc. Now assume a set abstraction having the operations contains(x) and insert(x) implemented using elastic transactions, and a programmer who wants to compose them to obtain the operation insertIfAbsent(x, y). This operation will insert x only if y is not present in the set. The programmer is now required to make a choice, to make or not the new transaction elastic, and he must choose wisely. If he chooses to make it elastic, the insertIfAbsent will not generate any conflicts based on its read-only prefix, including the entire contains(y) operation, as shown in Figure 1. If such conflicts are ignored, a concurrent transaction could insert y after the insertIfAbsent finds it absent but before inserting x. The result is an execution that violates atomicity. As an alternative, the model allows the programmer to make the insertIfAbsent a regular transaction, and thus lose the performance of having composed elastic insert and contains instead of ones implemented using regular transactions. Whatever the choice, either correctness or performance is sacrificed.

The motivation of this work is to determine whether relaxing the original transaction model inherently hampers composition. We believe the question to be fundamental because, without its ability to facilitate concurrent software composition, the transaction abstraction looses most of its appeal.

This paper starts by defining a framework to reason about the notion of concurrent composition of software. We believe this framework to be interesting in its own right since, to the best of our knowledge, the problem of concurrent composition has not been studied theoretically. In short, we propose a simple yet precise way to capture the very idea that one should be able to construct a new operation that invokes existing operations in sequence. Given that existing operations behave *correctly* in the face of concurrency, both new and old operations must execute *correctly* in a concurrent setting. In our context, the desired correctness criterion is atomicity.

To the best of our knowledge, the present paper is the first to clearly define a correctness criterion for composing relaxed transactions. We continue by presenting a property we call *outheritance*, which we show to be necessary and sufficient for ensuring composition of relaxed transactions. The property is defined using the notion of a *protected set*. Basically, every transaction t protects certain elements (memory locations, locks, etc.) in order to detect when atomicity might be violated. These elements form what we call the *protected set* of t. In a nutshell, outheritance stipulates that the protected set of the child transactions must be included in the protected set of the parent transaction, thus guaranteeing atomicity.

Concrete instantiations of the principle we call outheritance have been used before. Probably the most notable one is represented by classical transactions, using flat nesting. A classical transaction protects all the memory locations it accesses and after commit, they are protected by its parent transaction. However, we believe outheritance to be a general principle that can be used for ensuring atomicity of different types of relaxed transactions or even other synchronization mechanisms. Due to its simple formulation, outheritance can easily be used to check the composability of a relaxed transactional model, as well as when designing a new model, to ensure that it provides composition.

We show however that outheritance can be achieved without necessarily hampering concurrency and performance. We describe our new Software Transactional Memory (STM), called O$\mathcal{E}$-STM, which satisfies ouheritance while implementing the elastic transaction model [17]. (Outheritance is by no means tied to any specific transactional model and other models could have been considered instead of the elastic one). We compare our STM to three state of the art ones, TL2 [23], LSA [24] and SwissTM [25]. Our STM speeds up state-of-the-art STMs by up to 2.7$\times$ on a 64-hardware-thread machine.

The rest of the paper is organized as follows. Section II introduces our system model and Section III defines composition. Section IV presents outheritance and shows it to be necessary and sufficient for composition. Section V describes

the design of our new STM, which we used to build the transactional alternative to the concurrency package of the JDK described in Section VI. Section VII shows the performance of this package. Section VIII reviews related work and Section IX concludes the paper.

II. System model

Our transactional model builds upon that of Weihl [26], which we refine by introducing the notion of *protection element* that abstracts away the conflict detection mechanisms employed by relaxed transactional models. Using this we then proceed to define relax-serializability, a correctness condition for relaxed transactions, as well as a correctness criterion for composing these transactions.

For our purposes, a system is composed of processes and objects. *Objects* represent the state of the system; they provide operations through which processes executing transactions examine and change the system state. Objects are the only mean through which processes can pass information among themselves. We denote by $\mathcal{O}$ the set of objects in the system and for an object $o \in \mathcal{O}$, $o.ops$ is the set of operations provided by the object and $o.vals$ is the set of return values of these operations. *Processes* are sequential threads of control that change the state of the system by executing *transactions* supplied by a transactional memory. We denote by $\mathcal{P}$ the, potentially infinite, set of processes in the system.

We consider that a *transactional memory* exposes an interface allowing processes to start transactions, invoke operations on objects in the system, and finally attempt to commit the transaction. A transaction can either *commit*, making its changes visible to other transactions, or *abort*, in which case none of its changes are visible. Each transaction has a unique transaction identifier $t \in \mathcal{T}$, where $\mathcal{T}$ is the set of all transaction identifiers. The transactional memory guarantees serializability, or relax-serializability, as defined later in this section. Throughout this work we are interested only in transaction instances and, by abuse of notation, we refer to them simply as transactions.

As we are reasoning about the atomicity properties of a transactional memory system, we are interested in events that occur at the interface between the transactional memory and the objects. To make our reasoning simpler, we also consider virtual events representing the beginning, commit or abort of transactions. Thus we identify several types of events:

- process $p \in \mathcal{P}$ begins transaction $t \in \mathcal{T}$, written $\langle begin(t), p\rangle$;
- transaction $t \in \mathcal{T}$ invokes operation $op \in o.ops$ on object o, written $\langle op, o, t\rangle$;
- operation op of object o invoked by transaction $t \in \mathcal{T}$ terminates with result $v \in o.vals$, written $\langle v, o, t\rangle$;
- transaction $t \in \mathcal{T}$ executed by process $p \in \mathcal{P}$ commits, written $\langle commit(t), p\rangle$;
- transaction $t \in \mathcal{T}$ executed by process $p \in \mathcal{P}$ aborts, written $\langle abort(t), p\rangle$.

As we do not reason about progress properties of the transactional memory, we found no need to separate the $\langle begin(t), p\rangle$, $\langle commit(t), p\rangle$ and $\langle abort(t), p\rangle$ events into invocation and response pairs.

We model an observation of the system as a finite sequence of events and we use the $\cdot$ operator to denote sequence concatenation. We consider the virtual event $\langle begin(t), p\rangle$ to precede the first operation invocation performed by transaction t, while the $\langle commit(t), p\rangle$ virtual event follows the last response received by the transaction.

For a sequence of events H and an object $o \in \mathcal{O}$, we denote by $H|o$ the subsequence of H containing events involving object o. For a transaction identifier $t \in \mathcal{T}$ and a process $p \in \mathcal{P}$, we say that transaction t is executed by process p in event sequence H, if H contains the event $\langle begin(t), p\rangle$. We then denote by $H|p$ the subsequence of H containing the events involving transactions executed by p.

A sequence of events is said to be a *transaction* having transaction identifier t if:

- the first event is a $\langle begin(t), p\rangle$ for some process p;
- the next events are pairs of matching invocation and response events involving transaction t;
- the sequence ends with either a commit event $\langle commit(t), p\rangle$ or an abort event $\langle abort(t), p\rangle$.

Not all event sequences make sense as observations and as such we restrict our attention on sequences where for every process p that appears in H, $H|p$ can be extended by possibly appending a response and a commit event to a sequence of transactions. We refer to these "well-formed" sequences as *histories*.

For a history H, we define $transactions(H)$ to be the set of transactions t such that $\langle begin(t), p\rangle \in H$ for some process p. We then define $committed(H)$ to be the set of transactions t such that $\langle commit(t), p\rangle \in H$ and $aborted(H)$ as the set of transactions t such that $\langle abort(t), p\rangle \in H$. We also define $live(H)$ as the set $live(H) = transactions(H) \setminus (committed(H) \cup live(H))$. We denote by $committed\text{-}ops(H)$ the subsequence of H containing events that involve transactions $t \in committed(H)$. As we continue to reason about the correctness of committed and live transactions, we remove from histories all events involving aborted transactions.

In the same way as Weihl [26], we consider the *serial specification* $o.seq$ of an object o to model the acceptable behavior of the object in a sequential environment. If ω is a sequence of pairs $[op, v]$, with $op \in o.ops$ and $v \in o.vals$, then $o.seq$ is the set of all sequences ω that are considered acceptable behavior for the object in a sequential environment.

For an object o, a sequence ω of pairs $[op, v]$, with $op \in o.ops$ and $v \in o.vals$, is said to be *trivially commutative* if $\forall \omega', \omega''$ sequences of $[op, v]$ pairs of o, $\omega \cdot \omega' \cdot \omega'' \in o.seq$ if and only if $\omega \cdot \omega'' \cdot \omega' \in o.seq$.

For a history H and two events $e, e' \in H$, we denote the fact that e' *follows* e in H by $e \prec e'$. By abuse of notation, for two transactions $t, t' \in committed(H)$, if $\langle commit(t), p\rangle \prec \langle commit(t'), p'\rangle$ in H we also say that t' *follows* t in H and we denote it by $t \prec t'$. We say that t' *immediately follows* t in H and denote it by $t \prec^i t'$ if $t \prec t'$

and $\nexists t'' \in committed(H) \setminus \{t, t'\}$ such that $t \prec t'' \prec t'$ in H. We say that two transactions, t executed by process p, and t', executed by p', are *concurrent* in history H if $\langle begin(t), p\rangle \prec \langle begin(t'), p'\rangle$ and $\langle begin(t'), p'\rangle \prec \langle commit(t), p\rangle$ in H. History H is said to be *sequential* if no transactions are concurrent in H.

For a history H we denote by $ops(H)$ the subsequence of H containing all the operation events (invocations and responses). For a sequential history H, we define $opseq(H)$ to be the sequence obtained from $ops(H)$ by mapping all the matching pairs of invocation and response events $\langle op, o, t\rangle, \langle v, o, t\rangle$ to operation, value pairs $[op, v]$. To do the opposite, for an object o and transaction identifier t, we denote by $\omega \mapsto t$ the sequence of events obtained by converting every pair $[op, v] \in \omega$ to the pair of events $\langle op, o, t\rangle, \langle v, o, t\rangle$.

A sequential history H is said to be *legal* if for every object o that appears in H, $opseq(H|o) \in o.seq$. Two histories H and H' are said to be equivalent if for every process p, $H|p = H'|p$. A history H induces an irreflexive partial order $<_H$ on transactions in H: $t <_H t'$ if $\langle commit(t), p\rangle \prec \langle begin(t'), p'\rangle$ in H.

A history H is said to be *serializable* if there exists a legal sequential history S such that:

- $committed\text{-}ops(H)$ is equivalent to S, and
- $<_H \subseteq <_S$.

Note that we will be considering the strict form of serializability [27] for the course of this work.

A. The protection element abstraction

As classical transactional semantics proved too restrictive for concurrent data structures such as lists and trees [17], *relaxed transactions* have been designed to take advantage of the extra concurrency by ignoring some conflicts. To illustrate, consider a linked list along with an add operation that goes from the head towards the tail of the list and inserts an element at some position. Now an add operation implemented using a classical transaction is inserting an element somewhere in the middle of the list, while in the meantime another transaction is modifying the head of the list. In this situation, most implementations would cause one of the transactions to unnecessarily abort in order to avoid the complex detection of cycles in the conflict graph [14] and still guarantee serializability. However, an elastic transaction [17] would consider this to be a false conflict and hence allow both transactions to commit since semantically the execution does not violate atomicity. This type of transaction ignores conflicts caused by its read-only prefix.

In order to reason about relaxed transactions we introduce the notion of a *protection element*, an abstract entity used to model different existing conflict detection schemes. To each object $o \in \mathcal{O}$ we associate a protection element $\epsilon(o)$ that is *acquired* by transaction t before invoking an operation $op \in o.ops$. Transaction t will then *release* $\epsilon(o)$ when the conflict becomes benign. Between the acquisition of $\epsilon(o)$ by t and its release, we say that $\epsilon(o)$ belongs to the protected set of t, denoted by $P(t)$. Informally, a transaction maintains a protected set in order to detect conflicts between operations it has already applied and operations applied by other concurrent transactions. In Section IV we show that passing the protected set to the parent at commit time is a necessary and sufficient condition for ensuring composition.

We extend histories by adding two types of events: the acquisition of protection element $\epsilon(o)$ by process p, denoted by $\langle a(\epsilon(o)), p\rangle$, and the matching release event $\langle r(\epsilon(o)), p\rangle$. In order to be as general as possible, we only require that in any history H, the invocation and response of any operation $op \in o.ops$, invoked by transaction t executed by process p, be between a pair of acquire and next matching release event of protection element $\epsilon(o)$ by process p, $\langle a(\epsilon(o)), p\rangle \prec \langle op, o, t\rangle \prec \langle v, o, t\rangle \prec \langle r(\epsilon(o)), p\rangle$. We do not allow an acquire or release event between the last response event of a transaction t and the commit event of t.

In the case of classical transactions, the protection element associated with a memory location is acquired right before reading or writing the location and released after the commit of the transaction. In order to model transactional memories using deferred updates, we consider the protection element to be acquired at the point where the invocation was received by the transactional memory, even though the actual invocation on the object is performed at commit time. For modeling the early release mechanism of DSTM [15], the protection element is released when the release operation of the transactional memory is called, while for elastic transactions, it is released after a new protection element is acquired.

For a history H and a transaction $t \in committed(H)$ executed by process p, the *minimal protected set* of t, denoted by $P^{min}(t)$ is the set of protection elements $\epsilon(o)$ for which $\langle begin(t), p\rangle \prec \langle a(\epsilon(o)), p\rangle \prec \langle commit(t), p\rangle \prec \langle r(\epsilon(o)), p\rangle$. In other words, the minimal protected set contains the protection elements that are acquired by process p during the execution of transaction t and are not released at the time when t commits. We also define the *kernel* of transaction t as the set $ker(t) = \{o \in \mathcal{O} | \epsilon(o) \in P^{min}(t)\}$.

The notion of protection element is more general than a lock and it can model any way in which a transactional memory detects conflicts between transactions. For example, an invisible read also needs to acquire a protection element corresponding to the respective location, meaning that the transaction will recheck the location for consistency before committing, or until it releases the protection element.

The minimal protected set of a transaction t ensures that the abstract postcondition of t is not violated until the elements of the set are released. The content of this set does not depend only on the data structure and semantics of t but also on other transactions that can be executed concurrently. To illustrate, consider a set abstraction S, implemented with a linked list, where transaction t is performing an $\mathsf{insert}(x)$. If the only other possible concurrent transactions are some $\mathsf{remove}(x')$ and $\mathsf{contains}(x'')$, it is safe to consider $P^{min}(t)$ to be the element preceding x. The postcondition $x \in S$ cannot be violated without modifying the element preceding x. However, if we consider that a concurrent transaction can perform an

empty() operation that removes all elements from the list by setting the $head$ pointer to null, $P^{min}(t)$ must be reevaluated because the empty() operation can remove x without changing the element preceding it.

The reason for which operations sometimes need to acquire elements outside of their minimal protected set is that for many search structures such as lists, trees, graphs, etc., the minimal protected set is not known from the start and the operation needs to find the data and the elements from its minimal protected set.

B. Relax-serializability

For a history H and a protection element $\epsilon(o)$, we denote by $H|\epsilon(o)$ the subsequence of H containing the acquire and release events involving $\epsilon(o)$.

A history H is said to be *relax-serial* if for every protection element $\epsilon(o)$ that is acquired or released in H, the sequence $H|\epsilon(o)$ is a sequence of pairs of matching acquire and release events, starting with an acquire event. History H is said to be *relax-serializable* if there exists a legal relax-serial history S such that:

- $committed\text{-}ops(H)$ is equivalent to H, and
- $<_H \subseteq <_S$.

We say that a history H contains *relaxed transactions* if H is relax-serializable but not serializable. Note that since relaxation is a property of a history, we cannot say if a single transaction is relaxed or which transaction from a history is relaxed.

III. Composition

To better capture the intuition behind composition, we use as an example the Collection interface from the JDK, used to represent a group of objects. This interface has methods to add or remove elements from the group, check if an element belongs to the group, and so on, and is implemented by a number of classes such as HashSet, TreeSet, LinkedList, etc. Assume that a programmer, say Alice, starts writing a class implementing this interface, but she only implements the methods that she needs in her program, leaving the others as stubs. As such, Alice correctly implements add, remove and contains, but she does not implement others methods, such as addAll, that adds several elements to the group in a single atomic step.

Now a second programmer, Bob, gets the code written by Alice, wants to reuse it, but Bob also needs the addAll method. Bob quickly thinks that he can implement the addAll method by calling the add method for each of the elements that he wants to add and decides to use a loop to accomplish his task. Bob is relying on the correctness of the methods implemented by Alice but also on the fact that when he puts together these correct building blocks, the result is also correct. An important observation is that the newly created addAll method must behave as intended when other operations such as add and remove are executed concurrently. This issue is specific to concurrent programming.

As another example, Bob could use the add and remove methods written by Alice to implement a move operation that moves an element between two collections. Bob would again be relying on the fact that the whole, here the move, is equal to the sum of the parts, the add and remove. Bob would of course like his move operation to be able to run concurrently with instances of add and remove.

Our definition of composition captures the concept of creating a new operation by using existing operations as building blocks, and having the new operation invoke the existing ones. Starting with a set of atomic operations, the programmer would be able to compose them to obtain new atomic operations.

For a history H, a set of transactions $C \subseteq committed(H)$ is said to be a *composition* of process p if:

- all $t \in C$ are executed by p, and
- $\forall t \in C$, either $\exists t' \in C$ such that $t \prec^i t'$ in history $H|p$ or $\forall t' \in C \setminus \{t\}$, $t' \prec t$ in $H|p$; in the latter case, t is the supremum of C, denoted by $Sup(C)$.

Definition 3.1 (Strongly composable): Let H be a relax-serializable history and C a composition over H. H is said to be strongly composable with respect to C if H is equivalent to a relax-serial history S such that $\forall t_i, t_j \in C$ with $t_i \prec t_j$, $\nexists t_k \in committed(H) \setminus C, t_i \prec t_k \prec t_j$.

Informally, the above definition requires all transactions t_i and t_j from composition C to appear to execute one immediately after the other when observed from any object in the system. One might consider this to be a reasonable correctness condition for composing relaxed transactions. However, in the next section we show that this condition is too strong and therefore we relax it by only requiring t_i and t_j to appear one immediately after the other when observed from objects $o \in ker(t_i)$, a condition we call weak composability.

Definition 3.2 (Weakly composable): Let H be a relax-serializable history and C a composition over H. H is said to be weakly composable with respect to C if H is equivalent to a relax-serial history S such that $\forall t \in C$ and $\forall o \in ker(t)$, $\nexists t' \in committed(H) \setminus C$ such that $t \prec t' \prec sup(C)$ in history $S|o$.

If $\mathcal{C}$ is a set of compositions, a relaxed-sequential history H is said to be strongly (weakly) *composition-consistent* with respect to $\mathcal{C}$ if $\forall C \in \mathcal{C}$, H is strongly (weakly) composable with respect to C.

IV. Outheritance

We now define *outheritance* and, although it is not sufficient for ensuring strong composition (Theorem 4.2), we show it to be both necessary (Theorem 4.3) and sufficient (Theorem 4.4) for ensuring that a (potentially relaxed) transactional memory provides weak composition.

Definition 4.1 (Outheritance): A history H is said to satisfy outheritance with respect to composition C executed by process p if, $\forall t \in C$ and $\forall \epsilon(o) \in P^{min}(t)$, $\nexists e = \langle r(\epsilon(o)), p\rangle$ such that $\langle commit(t), p\rangle \prec e \prec \langle commit(Sup(C)), p\rangle$ in H.

Informally, outheritance prevents each protection element from the minimal protected set of each transaction in C from being released before the commit of the last transaction in C.

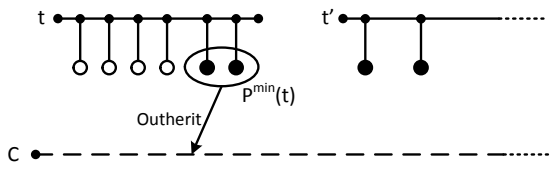


Fig. 2. Outheritance: minimal protected set is passed to the composed transaction.

For a transactional memory to satisfy outheritance, it needs to ensure that all the produced histories satisfy outheritance. This is done by making the transactions being composed pass their protection elements (be they locks or something else) to their parent transaction, which in turn will hold them until it commits.

Figure 2 shows transaction t passing its minimal protected set $P^{min}(t)$ containing two elements to composition C. These protection elements will not be released until the last transaction in C commits.

Some relaxed transactional models such as that of Felber et al. [17] do not satisfy outheritance and therefore can break composition. Indeed, one can compose two elastic transactions inside another elastic transaction, causing the protection elements of the first composed transaction to be released as soon as it commits instead of passing them to the resulting transaction, situation depicted in Figure 1. Since this practice can produce executions that are not atomic, the authors provide a workaround, namely by advising the programmer to predict these situations and use regular mode when composing.

A. Outheritance and strong composition

In this section we prove that outheritance is not a sufficient condition for ensuring that a relaxed transactional memory ensures strong composition.

Theorem 4.2: There exists a history H and a composition C over H such that H satisfies outheritance with respect to C but does not satisfy strong composition with respect to C.

Proof: We perform this proof by construction. History H contains three transactions, t_1, t_2 and t_3, with t_1 and t_3 executed by process p_1 and t_2 executed by p_2, and composition $C = \{t_1, t_3\}$. This situation is depicted in Figure 3.

Let history H be the following:

$$H = \langle begin(t_1), p_1\rangle, \langle a(\epsilon_1), p_1\rangle, \langle w(2), x, t_1\rangle, \langle ok, x, t_1\rangle,$$

$$\langle commit(t_1), p_1\rangle, \langle begin(t_3), p_1\rangle, \langle a(\epsilon_2), p_1\rangle, \langle inc(), c, t_3\rangle,$$

$$\langle 1, c, t_3\rangle, \langle r(\epsilon_2), p_1\rangle, \langle begin(t_2), p_2\rangle, \langle a(\epsilon_2), p_2\rangle, \langle inc(), c, t_2\rangle,$$

$$\langle 2, c, t_2\rangle, \langle commit(t_2), p_2\rangle, \langle r(\epsilon_2), p_2\rangle, \langle a(\epsilon_2), p_1\rangle,$$

$$\langle inc(), c, t_3\rangle, \langle 3, c, t_3\rangle, \langle r(\epsilon_2), p_1\rangle, \langle r(), x, t_3\rangle,$$

$$\langle 2, x, t_3\rangle, \langle commit(t_3), p_1\rangle, \langle r(\epsilon_1), p_1\rangle.$$

The sequence $H|\epsilon_1 = \langle a(\epsilon_1), p_1\rangle, \langle r(\epsilon_1), p_1\rangle$ contains a single pair of acquire and release events while the sequence

$$H|\epsilon_2 = \langle a(\epsilon_2), p_1\rangle, \langle r(\epsilon_2), p_1\rangle, \langle a(\epsilon_2), p_2\rangle,$$

$$\langle r(\epsilon_2), p_2\rangle, \langle a(\epsilon_2), p_1\rangle, \langle r(\epsilon_2), p_1\rangle$$

is a sequence of pairs of acquire and release events. We conclude that history H is relax-serial.

History H satisfies outheritance with respect to C since $P^{min}(t_1) = \{\epsilon_1\}$ and $\langle r(\epsilon_1), p_1\rangle$ is after $\langle commit(t_3), p_1\rangle$ in H. But in $H, t_1 \prec t_2 \prec t_3$. In order to show that history H is not strongly composable with respect to C we need to show that there is no legal relax-serial history H' equivalent to H such that $t_1 \prec^i t_3$ in H'.

History H is equivalent to history H' where $t_1 \prec t_3 \prec t_2$, but this implies $opseq(H'|c) = [inc, 1], [inc, 3], [inc, 2]$ and therefore $opseq(H'|c) \notin c.seq$ and H' is not legal. History H is also equivalent to history H'' where $t_2 \prec t_1 \prec t_3$, but this implies $opseq(H''|c) = [inc, 2], [inc, 1], [inc, 3]$ and $opseq(H''|c) \notin c.seq$ and therefore H'' is not legal.

We therefore can conclude that H is not equivalent to a legal relax-serial history in which $t_1 \prec^i t_3$, i.e. H is not strongly composable with respect to C and our proof is complete. ■

B. Ensuring weak composition

In this section we prove that outheritance is both necessary (Theorem 4.3) and sufficient (Theorem 4.4) for ensuring that a (potentially relaxed) transactional memory ensures weak composition.

Theorem 4.3: For any history H and any composition C over H such that $\exists t \in (C \cap live(H))$ and H satisfies outheritance with respect to C, if we extend H to history $H' = H \cdot \langle r(\epsilon(o)), p\rangle$ such that H' does not satisfy outheritance with respect to C and $opseq(H|o)$ is not trivially commutative, then H' can be extended to history H'' that is not weakly composable with respect to C.

Proof: If $H' = H \cdot \langle r(\epsilon(o)), p\rangle$ does not satisfy outheritance with respect to C while H does satisfy it, we deduce that $\epsilon(o)$ is part of the minimal protected set $P^{min}(t')$ of some $t' \in (C \cap committed(H))$.

Since $opseq(H|o)$ is not trivially commutative, there exist two sequences of operations of o, ω_o and ω'_o such that $opseq(H|o) \cdot \omega_o \cdot \omega'_o \in o.seq$ but $opseq(H|o) \cdot \omega'_o \cdot \omega_o \notin o.seq$. Hence we can append to H' a new transaction t'' executed by some process p', $\langle begin(t''), p'\rangle, \langle a(\epsilon(o)), p'\rangle \cdot \omega_o \mapsto t'' \cdot \langle commit(t''), p'\rangle, \langle r(\epsilon(o)), p'\rangle$. We can now complete transaction t by appending $\langle a(\epsilon(o)), p\rangle \cdot \omega'_o \mapsto t \cdot \langle commit(t), p\rangle, \langle r(\epsilon(o)), p\rangle$ to the resulting sequence and we obtain H''.

If H is equivalent to relax-serial history S, then H'' is equivalent to the history

$$S' = S \cdot \langle r(\epsilon(o)), p\rangle, \langle begin(t''), p'\rangle, \langle a(\epsilon(o)), p'\rangle \cdot \omega_o \mapsto t'' \cdot$$

$$\langle commit(t''), p'\rangle, \langle r(\epsilon(o)), p'\rangle, \langle a(\epsilon(o)), p\rangle \cdot \omega'_o \mapsto t \cdot$$

$$\langle commit(t), p\rangle, \langle r(\epsilon(o)), p\rangle$$

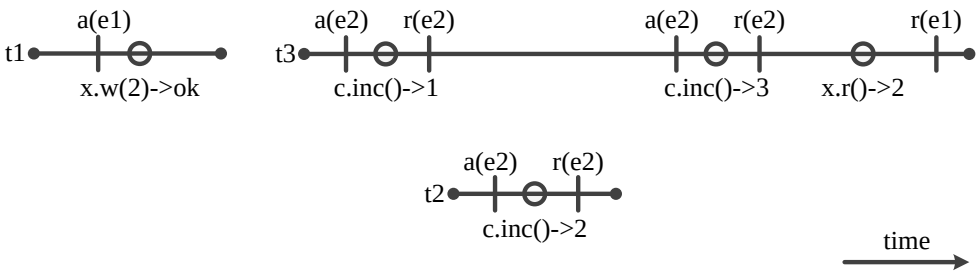


Fig. 3. Execution that satisfies outheritance but does not satisfy strong composition.

that is relax-serial but does not satisfy composition with respect to C since $t' \prec t'' \prec t$ in history $S'|o$.

History H'' is also equivalent to the history

$$S'' = S \cdot \langle r(\epsilon(o)), p\rangle, \langle a(\epsilon(o)), p\rangle \cdot \omega'_o \mapsto t \cdot \langle commit(t), p\rangle,$$

$$\langle r(\epsilon(o)), p\rangle, \langle begin(t''), p'\rangle, \langle a(\epsilon(o)), p'\rangle \cdot \omega_o \mapsto t'' \cdot$$

$$\langle commit(t''), p'\rangle, \langle r(\epsilon(o)), p'\rangle$$

and $t' \prec t \prec t''$ in history $S''|o$, but S'' is not legal since $opseq(S''|o) = opseq(H|o) \cdot \omega'_o \cdot \omega_o \notin o.seq$. ∎

According to Theorem 4.3, it is necessary for all histories produced by a transactional memory to satisfy outheritance in order to ensure composition.

Theorem 4.4: Any relax-serializable history H that satisfies outheritance with respect to composition C is weakly composable with respect to C.

Proof: We perform this proof by contradiction. Assume there exists a relax-serializable history H that satisfies outheritance with respect to C but is not weakly composable with respect to C.

If H is relax-serializable, then there exists a relax-serial history S equivalent to H. Since H is not weakly composable with respect to C, then $\exists t, t' \in C, t'' \in committed(H) \setminus C$, and $\epsilon(o) \in P^{min}(t)$ such that $t \prec t'' \prec t'$ in history $S|o$. If history H is not weakly composable with respect to C, then H is not equivalent to any legal relax-serial history S' such that $t'' \prec t \prec t'$ in history $S'|o$.

Since S is a relax-serial history and $\forall o \in ker(t), \langle commit(t'), p\rangle \prec \langle r(\epsilon(o)), p\rangle$, then $\nexists e = \langle a(\epsilon(o)), p'\rangle$ such that $\langle commit(t), p\rangle \prec e \prec \langle commit(t'), p\rangle$. Therefore $\nexists e' = \langle op, o, t'''\rangle$ such that $\langle commit(t), p\rangle \prec e' \prec \langle commit(t'), p\rangle$. It follows that in history $S|o$, $\nexists e'' = \langle op, o, t'''\rangle$ such that $commit(t) \prec e'' \prec commit(t')$. We conclude that history $S|o$ is equivalent to history S' where $commit(t''') \prec commit(t) \prec commit(t')$ and we have reached a contradiction. ∎

According to Theorem 4.4, it is sufficient for all histories produced by a transactional memory to satisfy outheritance in order for composition to be ensured.

C. The cost of composition

Oftentimes a programmer is faced with the problem of having to choose between several distinct options when implementing an operation. These distinct solutions come down to a choice between composing different operations to obtain the desired result. But not all compositions have the same cost. The cost of a composition of a process is a measure of the number of operations that other processes cannot execute due to this composition. By being able to compute the cost of a composition, the programmer can choose between distinct implementations of the same operation.

Let H be a history and C a composition of process p in H. If $\mathcal{H}_e$ is the set of all histories H_e such that $H_e|p = H|p$ and $\mathcal{H}_c$ is the set of all histories H_c such that $H_c|p = H|p$ that compose with respect to C, the cost of composition C will be

$$cost(C) = \frac{|\mathcal{H}_e|}{|\mathcal{H}_c|}$$

Intuitively, this cost is obtained by dividing the number of possible histories of the system when process p is executing transactions $t \in C$ to the number of histories where process p is executing the same transactions but are also composable with respect to C.

Since both $\mathcal{H}_e$ and $\mathcal{H}_c$ contain an infinite number of histories, we perform an approximation in order to obtain a simpler way of measuring the cost of composition C. For $t \in C$ and $o \in ker(t)$, let $H = H' \cdot \langle commit(t), p\rangle \cdot H''$ and $\omega = opseq(H'|o)$. We now define $\forall op_1, op_2 \in o.ops, \forall v_1, v_2 \in o.vals$, the set $\mathcal{N}_e$ of sequences $\omega \cdot [op_1, v_1], [op_2, v_2] \in o.seq$. We similarly define $\forall op_1, op_2 \in o.ops, \forall v_1, v_2 \in o.vals$, the set $\mathcal{N}_c$ of sequences $\omega \cdot [op_1, v_1], [op_2, v_2] \in o.seq$ such that $\omega \cdot [op_2, v_2] \cdot [op_1, v_1] \in o.seq$. Then the cost of composition C on object o is $cost(o) = \frac{|\mathcal{N}_e|}{|\mathcal{N}_c|}$. The cost of composition C then becomes

$$cost(C) = \sum_{t \in C} \sum_{o \in ker(t)} cost(o).$$

To illustrate, consider o to be a register supporting operations read and write and $\omega = \omega', [\mathsf{write}(5), ok]$. So the register holds the value 5 after operation ω is executed. Assuming it

can hold integers from 1 to n, the set $\mathcal{N}_e$ contains n^2 histories where both op_1 and op_2 are writes, n histories where op_1 is a write and op_2 is a read, n histories where op_1 is a read and op_2 is a write and one history where both op_1 and op_2 are reads, for a total of n^2+2n+1 histories. The set $\mathcal{N}_c$, containing histories from $\mathcal{N}_e$ where op_1 and op_2 commute, contains only n^2+3 histories. We compute a cost for composing a transaction that accesses this register to

$$cost(register) = \frac{\mathcal{N}_e}{\mathcal{N}_c} = \frac{n^2+2n+1}{n^2+3}.$$

V. O$\mathcal{E}$-STM

We briefly present here our software transactional memory, O$\mathcal{E}$-STM (Outheritance-Elastic STM) that allows programmers to compose transactions while preserving concurrency. It is largely based on $\mathcal{E}$-STM of Felber et al. [17], which we modified in order to satisfy outheritance and thus offer composition.

The elastic transaction model allows the programmer to use either an elastic or a regular transaction for implementing an operation, depending on the semantics of that operation. An *elastic transaction* ignores all conflicts induced by its read-only prefix, i.e., all conflicts involving its reads that precede its first write access. In the implementation, an elastic operation is executed optimistically and during its execution, an elastic transaction keeps track temporarily of the immediate past read accesses, but ensures that each read returns a consistent value. Upon writing, the transaction starts keeping track permanently of all accesses including the immediate past reads. At commit-time, the transaction can check that the access sequence it kept track of looks like being executed atomically and can decide to abort or commit accordingly. More precisely, if an operation π_i invokes only read operations, then the protected set of π_i is $P(\pi_i) = \{r_n\}$, where r_n is the last memory location read by π_i. Otherwise, if r_k is the first memory location written by operation π_i, the protected set is $P(\pi_i) = \{r_k, \ldots, r_n\}$, where r_n is the last memory location accessed by π_i.

In order to satisfy outheritance, elastic transactions must pass their protected set to their parent transaction when committing. More concretely, they need to add the read set as well as the last read memory location into the read set of the parent transaction and also add the write set to that of the parent. Figure 4 presents the pseudocode that needs to be added to $\mathcal{E}$-STM in order to satisfy outheritance. The outherit() function must be invoke by every transaction before invoking the usual commit function of $\mathcal{E}$-STM. This function first checks if the transaction has a parent, and if so, invokes the add-to-protected-set function of the parent, to which it passes the read set, last read location and the write set of the child transaction. The parent transaction then adds them to its read and write set.

```
1: outherit()_t:
2:   if t_parent ≠ ⊥ then
3:     t_parent.add-to-protected-set(read-set, last-read-entry, write-set)

4: add-to-protected-set(r-s, l-r, w-s)_t:
5:   r-set ← r-set ∪ r-s ∪ l-r
6:   w-set ← w-set ∪ w-s
```

Fig. 4: Changes to elastic transactions to satisfy outheritance.

VI. Illustration: a Java Transactional Package

We illustrate the importance of composition (and thus outheritance) for a relaxed transactional model by building a highly-concurrent Composable Java Package, called e.e.c (edu.epfl.compositional). Our solution provides composition, unlike the similar j.u.c (java.util.concurrent) package [6]. Our implementation performs very well compared to other composable alternatives, as shown in Section VII.

a) The java.util.concurrent package.: This package provides invaluable low level atomic primitives for concurrent programming, however, it is not composable and several of its methods violate atomicity. For instance, the JDK6 documentation describes the ConcurrentSkipListSet with "the bulk operations addAll, removeAll [...] are not guaranteed to be performed atomically" or describes the ConcurrentLinkedQueue iterator as "weakly consistent". This lack of atomicity makes the semantics of these methods hard to reason about. For example, the concurrent execution of removeAll and addAll that both take a Collection of integers 1 and 2 as a parameter may lead to an inconsistent state where only one of the two integers is present.

To compose the methods of these lock-free algorithms while preserving atomicity, the modifications could apply speculatively on some copy of the whole data structure before a current copy pointer could be compared-and-swapped from the former copy to the new one, provided that no concurrent accesses were executed. The time and space complexity of such a solution justified the implementation of non-atomic operations in java.util.concurrent.

The locking technique suggested in [28, Section 5.2.1] to circumvent this issue for the ConcurrentHashMap is evaluated in Section VII.

b) The edu.epfl.compositional package.: Figure 5 depicts the atomic operations add and addAll of SkipListSet as present in e.e.c, a skip list implementation of a set abstraction.

The first observation is that the add implementation is similar to its sequential counterpart: no locks or synchronization primitives are exposed to the programmer. What makes the code concurrent are the region delimiters begin[relaxed] and end indicating that the region should execute as a relaxed transaction. The rest of the code simply comprises assignments that rely on read and write accesses. All reads and writes are instrumented automatically as long as they appear in the delimited region. Section VII further details automatic transactional instrumentation in Java.

The addAll operation includes a series of accesses to add delimited by begin[regular] and end. These delimiters indicate that all read/write accesses have to be executed in the regular

SkipListSet

```
add(Value val)
  begin[relaxed]
      Node[] preds = new Node[topLevel+1];
      Node curr = head;
      Node next = curr.getNext(topLevel);
      for (int l = topLevel; l>0; l--) {
        next = curr.getNext(l);
        while (next.getVal() < val) {
          curr = next;
          next = curr.getNext(l);
        }
        preds[l] = cur;
      }
      if (next.getVal() != val) {
        node = new Node(getVal(), getRndLevel());
        for (int j=0; j<topLevel; j++) {
          node.getNext(j) = preds[j].getNext(j);
          preds[j].setNext(j, node);
        }
      }
      return (next.getVal() != val);
  end

addAll(Collection c)
  begin[regular]
        boolean result = false;
        for (Value x : c) result |= this.add(x);
        return result;
  end
```

Fig. 5: The pseudocode for operations add and addAll of SkipListSet of the e.e.c.

mode. Note that the original relaxed mode of add gets overwritten due to the priority of the regular mode of the outer operation and there is no need to change the existing code of add.

VII. Evaluation

We evaluate our transactional memory implementation, O$\mathcal{E}$-STM, using as benchmark the new Java package, edu.epfl.compositional (e.e.c), which we introduced in Section VI. In short, our e.e.c package is a composable alternative to the JDK concurrency package. This package provides basic operations, contains, add and remove, as well as operations resulting from the composition of these such as removeAll and addAll that are part of classes implementing the Java Collection interface. Although these composed operations tend to limit concurrency, due to their results depending on elements located at different places in the data structure, we show that our solution scales well with the level of parallelism and performs better than other STMs.

A. Experimental setting

We compare O$\mathcal{E}$-STM against bare sequential code, state-of-the-art STMs. We use an UltraSPARC T2 with 8 cores running up to 8 hardware threads each. For each run we averaged the number of executed operations per millisecond and aborts (for STMs) over 10 runs of 10 seconds each. We used Java SE 1.6.0_12-ea in server mode and HotSpot JVM 11.2-b01. All our workloads comprise 20% attempted updates on a data structure of 2^{12} elements. More precisely, each add/remove picks a value among a range of 2^{13} for a probability of success of $\frac{1}{2}$ and each addAll/removeAll takes one value v in the same range and takes a second value as the closest integer to $\frac{v}{2}$. The rest comprises 80% of contains.

B. Performance comparison

TL2 [23] is an efficient STM whose writes are not visible before commit-time and that uses timestamp intervals to validate transactions at commit-time; LSA [24] relies on a lazy snapshot algorithm that uses eager lock acquirement and extends this validity interval as much as possible to increase concurrency further; and SwissTM [25] builds upon LSA and mixes eager and lazy conflict resolution to abort as soon as possible while trying to maximize throughput.

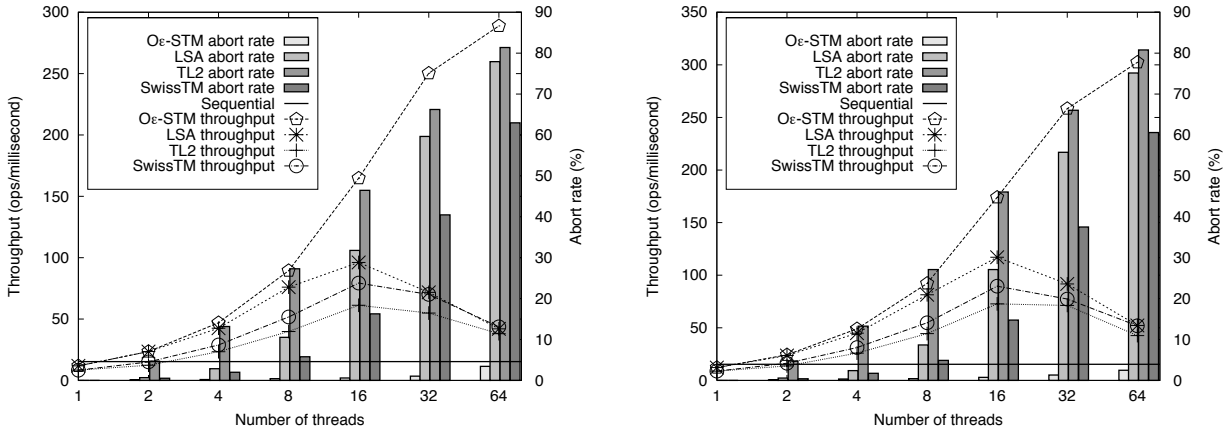
Our STM runtime relies on the use of the bytecode instrumentation framework Deuce developed by [29], which instruments delimited Java accesses by their transactional reads/writes defined by the transactional memory given as parameter. For the sake of comparison, we reused the existing Java version of LSA, TL2 and we implemented SwissTM and O$\mathcal{E}$-STM. To improve concurrency, all STMs protect memory locations at the granularity level of object fields.

We report on the throughput as the number of operations performed per millisecond and the abort ratio on three data structures, LinkedListSet (Figure 6), SkipListSet (Figure 7), HashSet (Figure 8). Interestingly, the throughput does not drop when increasing from 5% to 10% addAll/removeAll. O$\mathcal{E}$-STM has a higher throughput than other STMs at a high level of parallelism. O$\mathcal{E}$-STM presents similar performance as other STMs at low parallelism which may be due to the heavy metadata management of relaxed transactions.

The abort rate obtained on the linked list (Figure 6) is significantly higher for regular transactions (LSA, TL2, SwissTM) than for relaxed transactions which motivates the need for relaxed STMs ensuring composition, like O$\mathcal{E}$-STM. Consequently, O$\mathcal{E}$-STM has a much higher throughput on LinkedListSet than other STMs. Specifically, O$\mathcal{E}$-STM improves the performance of other STMs by at least $6.6\times$. This is due to the nature of the data structure whose linear time accesses are good candidates for concurrency optimization using relaxed transactions. Moreover, besides O$\mathcal{E}$-STM the STMs behave poorly as they almost never exceeds sequential performance (normalized throughput remains below 1).

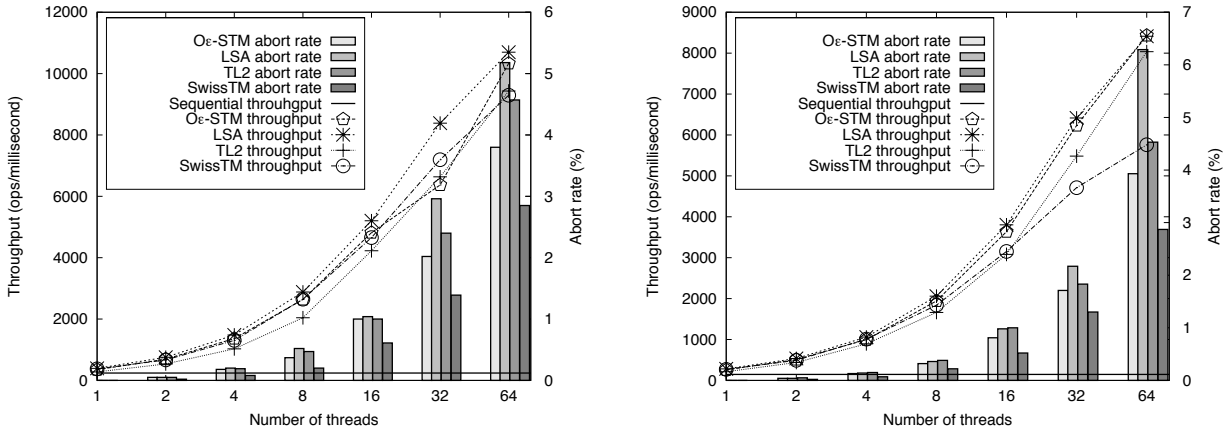
Only on the SkipListSet performs one STM comparably well to O$\mathcal{E}$-STM. In this particular workload the transaction relaxation does not benefit much the performance. The reason is that each update may modify $(O(\log n))$ nodes inducing a contention that relaxation cannot avoid. Also, the benefit is proportional to the number of traversed nodes per transactions, which is much lower than a linear data structure like the linked list. Finally, O$\mathcal{E}$-STM performs much better than other regular STMs on the HashSet (Figure 8) whose load factor (i.e., number of nodes / number of buckets) is set to 512 to increase the contention.

To conclude, O$\mathcal{E}$-STM, which composes like regular STMs, present better performance than them because it provides relaxed transactions that diminishing contention when the application permits.



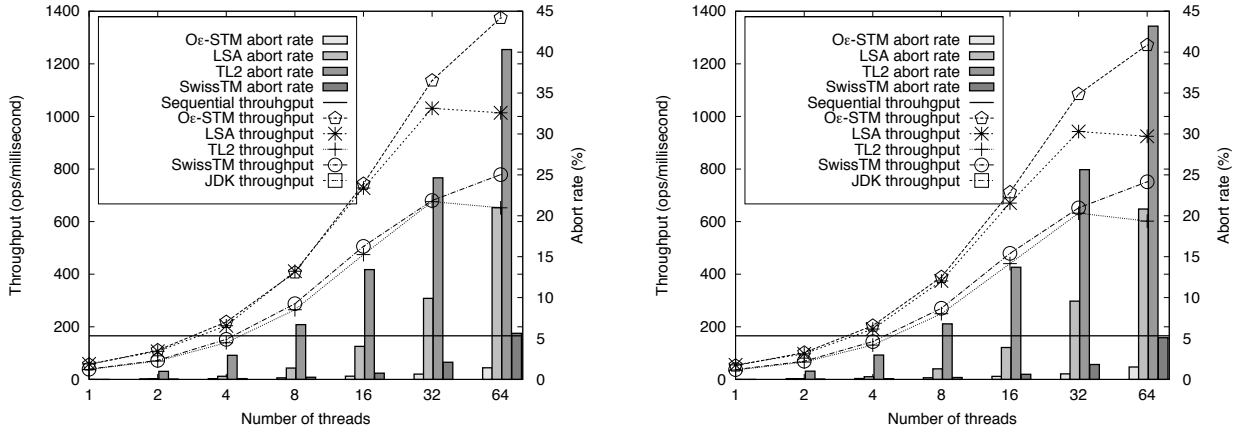
(a) 5 % update (b) 15 % update

Fig. 6: Throughput and abort ratio of bare sequential code, O$\mathcal{E}$-STM, LSA, TL2 and SwissTM on the LinkedListSet of e.e.c when running 5% (left) and 15% (right) of addAll/removeAll.



(a) 5 % update (b) 15 % update

Fig. 7: Throughput and abort ratio of bare sequential code, O$\mathcal{E}$-STM, LSA, TL2 and SwissTM on the SkipListSet of e.e.c when running 5% (left) and 15% (right) of addAll/removeAll.



(a) 5 % update (b) 15 % update

Fig. 8: Throughput and abort ratio on the HashSet of java.util, throughput and abort ratio of bare sequential code, O$\mathcal{E}$-STM, LSA, TL2 and SwissTM on the HashSet of e.e.c when running 5% (left) and 15% (right) of addAll/removeAll.

VIII. Related Work

The problem of composition objects with certain properties to obtain atomic transactions was studied by Weihl [26]. Unlike his work, we compose relaxed transactions in order to obtain new transactions that are also relaxed. For this we consider relax-serializability, a condition that is strictly weaker than classical serializability.

Transactional boosting [30] is a transactional model where objects are not only reads/write registers as in classical transactional memories, but also objects implemented in a separate thread-safe library. In order to detect conflicts between these operations, abstract locks are used. To convert this to our model, one would acquire the protection element of an object o whenever a transaction acquires an abstract lock corresponding to object o. Since on rollback it is not sufficient to restore the memory to the state before the start of the transaction, the programmer must define a compensating operation for every operation executed by the transaction. Although not described in the paper, passing abstract locks from the child to the parent transaction would make transactional boosting satisfy outheritance and therefore compose.

Open nesting [16] is a relaxed transactional model that allows the programmer to define open transactions that use abstract locks for providing multi-level conflict detection. As in the case of transactional boosting, each open transaction has an abort handler that reverts its effect in case of rollback. As this solution does not satisfy outheritance, no guarantees of atomicity are given and the programmer is responsible for ensuring correctness. The authors do however give guidelines to the programmer for ensuring atomicity when using open nesting. In order to accommodate for multi-level concurrency control, one would add, for all the abstract locks protection elements that are acquired and released at the same time as abstract locks. In these conditions, outheritance would still guarantee relax-serializability at the lower level, but one could violate outheritance and still obtain the desired correctness of higher level transactions.

View transactions [20] are a type of relaxed transactions that define the critical view of a transaction, similar our minimal protected set, by using programmer specified view pointers. When committing, view transactions can pass their critical view to their parent transaction, thus satisfying outheritance and correctly composing.

Kulkarni et al. [31] provide yet another concrete instantiation of our principle, outheritance, this time passing the protected set from a child to the parent in the context of automatic parallelization. By satisfying outheritance, their approach ensures correct composition.

The classical way of using a transactional memory to obtain a thread-safe implementation of some abstract operation is to have every access to shared data performed by the implementation instrumented by the transactional memory. Bronson [32] proposed solutions where only some accesses to shared data are transactional, while others are performed using synchronization from a separate thread-safe library. When composing such an implementation, the transactional memory passes information about the transactional accesses to the parent transaction as required by outheritance, allowing the operations to compose correctly.

Chandy and Sanders [2] reason about parallel composition by extending predicate transformer theory to concurrent programming. They find some properties to be *all-component*, meaning that if all the components have the property, then their composition will have it as well, while other properties are *exists-component*, if at least one component has the property, then their composition will as well.

Gössler and Sifakis [3] describe a parallel composition operator that preservers deadlock-freedom. They distinguish between composability, the property of a component to meet a given property after being composed, and compositionality, which allows one to infer properties of a system from its components' properties. Our work falls in the latter category, namely one can infer the atomicity of composed operations from the atomicity of their sub-operations. This inference is valid when the system satisfies outhritance, which is in essence a concurrent composition operator.

Gava and Garnier [33] present a practical parallel composition operator using a continuation-passing-style transformation. This composition operator, useful for divide-and-conquer style algorithms among others, can be used many times in a single program, making an efficient implementation crucial. In the same vein, an efficient concurrent composition based on our outheritance principle has the potential of being widely used in concurrent programming.

Fei and Lu [34] have studied composition in the context of scientific workflows. They provide a workflow composition framework in which workflows are the only operands for composition, as well as workflow constructs such as Map and Reduce. An easy programming model featuring straightforward composition has the potential of being the go-to solution for scientific computing.

IX. Concluding Remarks

Transactional memory is commonly advertised as an appealing abstraction to bring concurrency to the *masses*. It hides the difficult challenges of synchronization and makes it possible for *inexperienced* programmers to compose concurrent software. This appealing view conveys however a dumbing down of the programmers, for composition, at least in its classical implicit and transparent sense, is possible only if all programmers use transactions. Certain programmers are however skilled enough to seek less transparent concurrency abstractions that boost efficiency by enabling interleavings that would be prevented by the original transactional scheme. Relaxed transactional models are such abstractions. While boosting concurrency, their usage jeopardizes the composition dream.

This paper describes outheritance, a concrete property for ensuring that a transactional memory providing relaxed transactions composes. Using it, one can easily see if a given transactional memory ensures composition or can build a new one

that does provide it. In short, outheritance stipulates that child transactions must pass their conflict information to their parent transaction, which in turn maintains it until commit time. As outheritance does not add any false-conflicts, if the original transactions do not manifest false-conflicts, nor does their composition. However, the number of false-conflicts is not the only factor that affects performance, but also the time duration for which a certain location can cause conflicts. Part of our future work includes a better understanding of the relationship between false-conflicts, composition and performance.

It is also important to notice that outheritance is not tied to any specific type of relaxation and can be used for building a transactional memory providing different types of relaxed transactions [35]. Another direction for future work consists of using outheritance for composing multiple types of relaxed transactions.

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