On the Correctness of Optimistic Composable Data Structures

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1 Introduction

Concurrent data structures are widely used in multithreading applications as they efficiently enable the exploitation of parallelism especially when deployed on multi-core architectures. Intuitively, the (complex) fine-grained design of a data structure [10, 9, 6, 3], in which only the critical part of an operation is synchronized, provides better performance than the (simpler) coarse-grained design where operations act in mutual exclusion. Moreover, there is a growing interest (e.g., [1, 7, 8, 17]) on composing data structure operations into a single transaction, rather than considering them as standalone atomic operations. This is mainly because *Transactional Memory* [5] (TM), the recent appealing programming abstraction for developing concurrent applications, has been integrated into commodity hardware chips [15, 2] and well-known compilers (e.g., [16]). This integration allows the usage of in-memory transactions to all programmers, including those non-experts. As one of the consequences of that, a programmer can easily wrap multiple data structure operations into a single atomic transaction, which thus enables *composability*.

The design of a data structure has its own challenges that depend on its semantics and implementation constraints. That is why, for the last decade, proving the correctness of most concurrent (and composable) data structures followed an ad-hoc approach. This lack of generality contributed to make the task of assessing their correctness very challenging. Recently, we observed an initial step towards accomplishing the goal of having a general model for proving the correctness of concurrent data structures, which is the *single writer multiple readers* model (we name it *SWMR* hereafter) presented by Lev-Ari et. al. in [13]. The *SWMR* model focuses on two safety properties (roughly summarized here): *validity*, which guarantees that no "unexpected" behaviors (e.g., access to an invalid address or a division by zero) can occur in all the steps of a concurrent execution; and *regularity*, an extension of the classical regularity model on registers [12] that guarantees that each read-only operation is consistent (i.e., linearized) with all the write operations. The appealing advantages of the *SWMR* model are that: *i)* it allows the programmer to use general and well defined terms (i.e., *base conditions* and *base points*) to prove the *validity* and *regularity* of any data structure fitting the *SWMR* model; and *ii)* it gives a formal way to prove *linearizability* [11] by relying on *regularity*.

Despite the strengths of the *SWMR* model, the set of data structures that can actually benefit from it does not include most of the recent highly optimized and practical concurrent [9, 6, 3] and composable [1, 7, 8, 17] data structures which, in addition, allow concurrent writes. Fortunately, those recent data structures have some common design principles that we can isolate. Specifically, in all the former examples, each update operation is split into a *read-only* traversal phase and a *read-write* commit phase, and the *traversal* phase is optimistically executed in isolation from the *commit* phase (and usually without monitoring its steps), counting on the fact that the output of the traversal phase remains "valid" during the *commit* phase. Given their optimistic nature, we name them as *optimistic data structures*.

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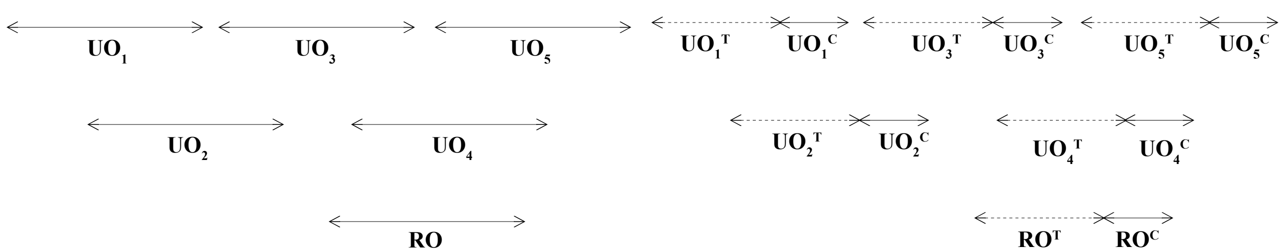
In this presentation, we focus on the class of *optimistic data structures* and we provide a set of models for assessing their correctness so that existing and future practical implementations can rely on that. The overall goal of those models is to provide a general approach (which uses the notion of *base points* and *base conditions* as *SWMR*) for proving the correctness of a set of data structures that allow *multiple writers multiple readers* (*MWMR*) executions, which are wider and more practical than the set of data structures fitting the *SWMR* model.

2 The Single Writer Commit (SWC) Model

As mentioned before, in our models each operation is split into *read-only traversal* phase and *read-write commit* phase. This representation is general enough to cover also those operations with either an empty traversal (i.e., operations whose first step is a write) or an empty commit phase (i.e., read-only operations).

We start by presenting the Single Writer Commit (SWC) model, a *MWMR* model in which both *read-only* and *update* operations run concurrently with the restriction that only the *commit* phases are atomically executed with the *Single Lock Atomicity (SLA)* semantics [14] (i.e., as if they are executed sequentially). For the sake of simplifying the presentation, we first introduce this model by assuming that the commit phases are protected by a single global lock, then we discuss the case of concurrent commits.

Figure 1 shows an example of this case with five *update* operations, $uo_1, ..., uo_5$, and one *read-only* operation ro. In this example, the commit phases of all the *update* operations do not interleave, even if the operations themselves interleave. The *read-only* operation ro is concurrent with uo_3, uo_4, and uo_5. In particular, it interleaves with the commit phases of uo_3 and uo_4, while its *commit* phase only interleaves with uo_4.



(a) Multiple Writers (b) Single Writer Commit

Figure 1: An example of a *MWMR* concurrent execution (a) that can be executed using our model by converting it to a *Single Writer Commit* scenario (b).

Figure 2(a) shows how we model a typical *optimistic data structure* operation. Any operation O is split into two sequences of steps: $O^T = s^1 \cdot ... \cdot s^m$; and $O^C = s^{m+1} \cdot ... \cdot s^n$. The sequence O^T represents the *traversal* phase, which does not contain any $write$ step. The sequence O^C represents the *commit* phase, which always ends with $return_O(v_{ret})$ and can contain both $read$ and $write$ steps. Given that a data structure under the *SWC* model allows concurrent *traversal* phases and a single *commit* phase at a time, the transitions from the *shared traversal* phase to the *exclusive commit* phase and vice versa are represented by two auxiliary steps S' and S'' (e.g., they can be an acquisition/release of a global lock). We do not assume the presence of such a transition in *read-only* operations, thus, in those cases, S' and S'' are just dummy steps that do nothing. Excluding the auxiliary steps, the commit phase of a read-only operation O is $O^C = return_O(v_{ret})$.

In practice, *optimistic data structures* usually start the *commit* phase by a validation mechanism to ensure that the output of the traversal phase remains valid until the transition to the exclusive *commit* mode; otherwise the *traversal* phase is re-executed. That is why it is important to include this re-execution mechanism in our model. To do so, we define for each operation O on a data structure ds a variable u that represents the number of *unsuccessful trials* ($u \in \{0, 1, ..., \infty\}$)[1]. The value of u is determined according to the design of ds and

[1]If for an operation O it is possible to have an execution with $u = \infty$, this (informally) entails that the operation is not wait-free.

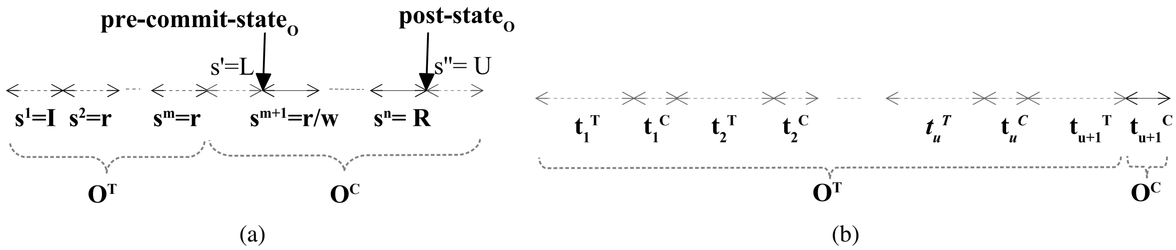


Figure 2: *a)* Splitting the operation to support concurrent MWMR execution with Single Writer Commit (SWC). O^T is the *traversal* phase; O^C is the *commit* phase. I:*invoke*, r:*read*, w:*write*, R:*return*, L:*lock*, U:*unlock*. *b)* Unsuccessful trials are part of the overall *traversal* phase in our model.

the concurrent execution μ that includes O. Every unsuccessful trial resets the local state (i.e. the values of the operation's local variables) of the operation to the initial $\perp$ state before starting the next trial. The commit phases of all the unsuccessful trials are clearly not allowed to write on the shared memory because of their inconsistent local state. As shown in Figure 2(b), the *traversal* phase of the operation O includes all those unsuccessful trials and the *commit* phase of O is only the successful *commit* phase of the last trial (${t_{u+1}}^C$).

Under such a model we define two states for each update operation u: $pre\text{-}commit\text{-}state_u$, which represents the local state of u after the auxiliary step s' and before the first *real* step in the *commit* phase, s^{m+1}; and $post\text{-}state_u$, which is the shared state of the data structure (i.e. the values of its variables) after the last step of u. Then we enforce that for every update operation u_i in a concurrent execution μ, $pre\text{-}commit\text{-}state_{u_i}$ observes $post\text{-}state_{u_{i-1}}$, where u_{i-1} is the update operation whose commit phase precedes the commit phase of u_i in μ.

The main idea of modeling data structures and concurrent executions in this way is that we can redefine the notion of *base points* and *base conditions* by following the main idea presented in [13]. Doing so we provide the programmer with a general methodology to prove the correctness of a generic MWMR data structure by identifying the *base conditions* associated with the steps of its operations.

By correctness here we mean $validity$, namely the execution of every step on a data structure ds is never subject to "bad behaviors" (e.g., division by zero or null-pointer accesses), and $regularity$, namely for each history H on ds, the sub-history composed of all write operations in H enriched with one read-only operation (if any) in H is linearizable.

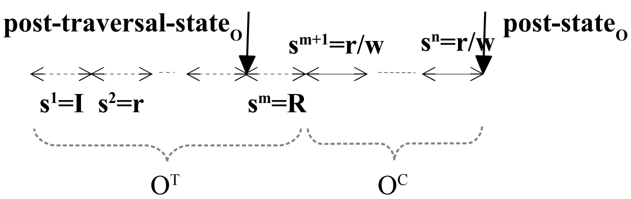
2.1 Allowing Concurrent Commits

The implementation of *optimistic data structures* usually do not rely on a global lock-based mechanism to finalize the writes, but rather, in order to increase the level of concurrency, the *commit* phase either executes inside TM transactions (hardware or software) [17, 1], or leverages the locking mechanism with *fine-grained* locks that protect (at least) the written locations [9, 10]. Fortunately, some of those techniques provide the same atomicity guarantees as global locks. For example, some TM implementation provides *single lock atomicity (SLA)* guarantees [14] (e.g., the HTM transactions provided by Intel's TSX extensions [15] and the SLA version of NORec [4]). By definition, *SLA* guarantees that all the non-transactional reads observe the same serialization of all the concurrent transactions. Thus, if those TM are used to execute the *commit* phases instead of serializing them with a global lock, then we can easily prove that the same guarantees are fulfilled. In fact, in [14] the authors formally prove that executing atomic blocks with *SLA* semantics is equivalent to executing them using *synchronized* blocks protected by a single lock, which implies that our model is safe under this new assumption.

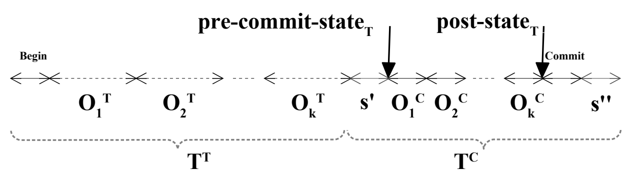
3 The Composable Single Writer Commit (C-SWC) Model

We now extend our model by allowing the composition of multiple operations into atomic transactions. For the sake of simplicity, we assume that all the operations belong to the same data structure, and then we remove this assumption by showing that operations on different data structures can be executed in the same transaction under the C-SWC model as long as the data structures are independent.

In the *C-SWC* model, as shown in Figure 3, each operation O_i is split into *traversal* (O_i^T) and *commit* (O_i^C) phases, and the transaction itself is split into a *traversal* phase that combines all the traversal phases of the operations (i.e., $T^T = start \cdot O_1^T \cdot O_2^T \cdot ... \cdot O_k^T$), and a *commit* phase that combines all the commit phases, surrounded by two auxiliary steps to move the execution to/from the exclusive mode (i.e., $T^C = S' \cdot O_1^C \cdot O_2^C \cdot ... \cdot O_k^C \cdot commit \cdot S''$). Like *SWC*, we assume for simplicity that *commit* phases are protected by a single global lock. However, the same arguments adopted in *SWC* can be applied here to consider concurrent executions under the *SLA* semantics. We also assume that the *commit* phases of transactions are the successful ones, and any unsuccessful trial is included in the transaction *traversal* phase.



(a) Operation split



(b) Transaction split

Figure 3: Splitting operations and transactions in the C-SWC model.

Figure 3 shows how operations are split in the *C-SWC* model. First, the *return* step of each operation is shifted to be the last step of its *traversal* phase. This is important because the return value of the operation may be used later in the transaction body. Second, the auxiliary steps S' and S'' are removed from the *commit* phases of operations and they appear only once in the *commit* phase of the enclosing transaction. Finally, a dummy step $s^{ro-commit}$ is added to the *commit* phase of any *read-only* operation ro. This dummy step becomes the only one in the *commit* phase of ro because the real *return* step is shifted to the *traversal* phase (as said before).

As shown in Figure 3, we define for each operation O_i one more state called $post\text{-}traversal\text{-}state_{O_i}$, which is the local state before O_i's *return* step. We also define for the whole transaction T a state called $pret\text{-}commit\text{-}state_T$ which is the local state after s'.

Analogously to the SWC case, under *C-SWC* we enforce that for every update transaction T_i in a transactional execution μ, $pre\text{-}commit\text{-}state_{T_i}$ observes the $post\text{-}state_{T_{i-1}}$, where T_{i-1} is the transaction whose commit phase precedes the commit phase of T_i in μ. By doing so we redefine the notion of *base points* and *base conditions* by starting from the definition provided in the SWC model. Therefore we provide the programmer with a general methodology to prove the correctness of a transactional MWMR data structure by identifying the *base conditions* associated with the steps of its operations.

By correctness here we mean *i)* $validity$, namely the execution of every step on a data structure ds is never subject to "bad behaviors" (e.g., division by zero or null-pointer accesses); *ii) internal consistency* which means that the return steps of the operations in the same transaction observes the same shared state, and can be informally defined as follows: the $post\text{-}traversal\text{-}states$ of every operation in a transaction T have the same *base point* as $pre\text{-}commit\text{-}state_T$. *iii)* and a variant of $regularity$ applied to transactional histories, and that we can informally define as follows: for each transactional history H on ds, the sub-history composed by all the committed *update* transactions in H plus another transaction in H (i.e., either read-only or update and either live/aborted or committed) is strict serializable.

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