

Automatic Optimistic Synchronization for Dynamic Data Structures

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1 Introduction

2 Preliminaries

A *module* defines a set of *abstract data types* and a set of *operations* that may be invoked by clients of the module. Each operation is invoked with possible parameters and returns with a response. The invocation is a local step of a thread, followed by a execution of a sequence of atomic steps. Atomic step is either a computation on local variables or a primitive operation on shared variable. Read and write to shared memory are denoted load and store. The parameters and local variables of an operation are private to the invocation of the operation (thread local). There are no static or global variables shared by different invocations of the operations.

A *configuration* is an instantaneous representation of the system, including the state of the shared memory and the local variables. In the *initial configuration* all variables hold an initial value. An *execution* is an alternating sequence of configurations and steps, $C_0, s_1, \dots, s_i, C_i, \dots$, where C_0 is the initial configuration, and each configuration C_i is the result of executing step s_i on configuration C_{i-1} .

An execution is *non-interleaved* (abbreviated NI-execution) if primitive operation of different operations are not interleaved, i.e., for every pair of operations invocations $p_i \neq p_j$ either all primitive operations of p_i come before any primitive operation of p_j , or vice versa.

Given an execution, we say that two primitive operations *conflict* if (i) they are executed by two different threads, (ii) they access some common global variable or a heap allocated object (iii) at least one of the conflicting instruction is a write.

Executions π_1 and π_2 are *conflict-equivalent* if they include the same primitive operations and they agree on the order between conflicting operations. An execution is *conflict-serializable* if it is conflict-equivalent with a non-interleaved execution.

3 Automatic Optimistic Synchronization

We address the problem of adding an optimism to a pessimistic locking protocol. Given a sequential implementation and some pessimistic locking protocol, that performs store steps only to locked objects, we add optimistic synchronization. The idea of optimistic synchronization is to load shared variables without locks and start using the locking protocol only when the operation reaches a store step. In practice our algorithm shows that there is no need to acquire locks if they are freed before any change is made.

This optimistic scheme separates the operation to three *phases*, an optimistic *read phase*, a pessimistic *read-write phase* and a *validation phase* that connect them.

3.1 Requirements on The Locking Protocol

In order for our algorithm to work, the initial locking protocol must have one of the following properties:

LPR1 The protocols allows early lock release.

LPR2 The protocols requires that all locks are acquired before the first store step.

For example the *two phase locking (2PL)* protocol does not allow early lock release (no locks can be acquired after a lock was released), also, it does not require acquiring all locks before the first store operation. However, a stricter version of 2PL locking that requires **LPR2** can be used to achieve optimism. The resulting optimistic protocol would be similar to *Transactional Locking 2*[1].

3.2 Detailed Algorithm

Each objects maintains a counter, incremented every time the object is locked. This counter is used to validate the correctness of the optimistic read phase.

Read Phase Starts at the beginning of the operation and ends at any point before the first store operation. During this phase the operation maintains a `read_set`, containing references to objects loaded and the local version when it was read. The local versions are incremented during the read-write phase, when the object is locked. Incrementing the version is not atomic with the lock, thus, the object is also checked to be unlocked. The read phase does not validate reads, in order to avoid infinite loops, a timeout is set. If the operation reaches the timeout, a `read_set` validation takes place, if it fails the operation restarts from the beginning. A pseudo code of the transformation can be found in Figure 1.

Validation Phase This phase connects the read phase with the read-write phase. It has two requirements: (i) lock local variables of the operation and (ii) ensure that the values read during the read phase are consistent,

<pre> 1: function FOO(...) ... 2: x = ptrExp ... </pre>	<pre> 1: temp = ptrExp 2: version = temp.getVersion() 3: if y.isLocked() then 4: goto 1 ▷ Restart Operation 5: readSet.add(temp,version) 6: x = temp </pre>
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Figure 1: Read phase transformation, the code in line 2 is replaced with the code on the right.

```

1: function FOO(...)
  ...
                                     ▷ begin read_set validation
2:   for all (ref,version)∈ readSet do
3:     if ref.isLocked() and ref.lockedBy!= self then
4:       goto 1           ▷ Restart Operation
5:     if version!= ref.getVersion() then
6:       goto 1           ▷ Restart Operation
  ...

```

Figure 2: read_set validation

i.e. as if the values were read while executing the locking protocol. To avoid deadlocks, the locks are acquired using a `try_lock` operation, if the `try_lock` fails, the operation restarts from the beginning. Next, the `read_set` is validated, if the validation fails the operation restarts from the beginning. During the `read_set` validation, each reference saved in the `read_set` is checked to be unlocked and that the current version matches the version saved in the `read_set`. A pseudo code of the `read_set` validation can be found in Figure 2.

Read-Write Phase This phase enforces the locking protocol while maintaining the local versions, i.e., the local version of an object is incremented every time it is locked. Once the read-write phase begins, the operation is guaranteed to finish without restarts.

The use of timeout does not guarantee *opacity* [2] or *validity*[3].

4 Algorithm's Correctness

We will prove that if the original locking protocol is conflict-serializable then our algorithm is conflict-serializable.

Let π be an execution of our optimistic automation on a sequential algorithm. We will construct an execution π_{LP} which is an execution following the original locking protocol. We will prove that both executions are conflict-equivalent.

Since any execution of the original locking protocol is conflict-serializable, then π is conflict-serializable.

Let p_1, p_2, \dots, p_n be the operations $\in \pi$ ordered by the order of execution of the first step of a successful `read_set` validation. (If some operation does not have such point we omit it). Let $\pi_{LP} = \pi_{lp1}, \pi_1, \dots, \pi_{lpi}, \pi_i$ where π_{lpi} is a p_i -only execution of original locking protocol until p_i holds locks only on the local variable locked in the validation phase of $p_i \in \pi$, and π_i is the interval of π starting from the return from the validation of p_i until the first step of the successful `read_set` validation of p_{i+1} that includes only the operations by $\{p_1, \dots, p_i\}$. In other words, we replace the read-phase and validation phase with an execution of the original locking protocol, taking place at the point just before the `read_set` validation starts.

Lemma 4.1 *The construction of π_{LP} is feasible.*

Proof Proof by induction on p_1, p_2, \dots, p_n . Base case is immediate.

Let $\pi' = \pi_{lp1}, \pi_1, \dots, \pi_{lpk-1}, \pi_{k-1}$ be the feasible construction so far, and let p_k be the next operation to be added.

Assume by contradiction that $\pi' \cdot \pi_{lpk} \cdot \pi_k$ cannot be constructed, thus, some object v that p_k locks in π_{lpk} is already locked by $p_j \in \{p_1, p_2, \dots, p_{k-1}\}$ in the last configuration of π' . If p_j locked v before p_k read v for the first time, then v was locked during the read phase of p_k , in contradiction to p_k reaching its validation. Otherwise, p_j locked v after p_k read v . If v is still locked during the validation of p_k then the validation will fail, contradiction. Alternatively, v was unlocked by p_j before p_k validated v , its version incremented to a version bigger than the local version read by p_k , contradicting the successful validation of p_k . ■

Lemma 4.2 *π_{LP} is conflict-equivalent to π*

Proof Each operation performs a double collect on all the values it reads. The first collect is the read phase and the second is the `read_set` validation of the validation phase. Since validation was successful, both collect are identical, meaning that the values of the `read_set` do not change from the return of the last read of the read phase, until the first read of the `read_set` validation. Therefore, executing the original locking of p_k after $\pi' = \pi_{lp1}, \pi_1, \dots, \pi_{lpk-1}, \pi_{k-1}$ is conflict-equivalent to the original read phase. The read-write phase remains unchanged, maintaining conflict-equivalence to π . ■

References

- [1] David Dice, Ori Shalev, and Nir Shavit. Transactional locking ii. In *DISC*, pages 194–208, 2006.
- [2] Rachid Guerraoui and Michal Kapalka. On the correctness of transactional memory. In *PPOPP*, pages 175–184, 2008.

- [3] Kfir Lev-Ari, Gregory Chockler, and Idit Keidar. On correctness of data structures under reads-write concurrency. In *DISC*, October 2014.