Opacity of Memory Management in Software
Transactional Memory

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Abstract. Opacity of Transactional Memory is proposed to be established by incremental validation. Quiescence in terms of epoch-based memory reclamation is applied to deal with doomed transactions causing memory access violations. This method unfortunately involves increased memory consumption and does not cover reclamations outside of transactions. This paper introduces a different method which combines incremental validation with elements of sandboxing to solve these issues.

Keywords: transactional memory, opacity, privatization, memory reclamation

1 Introduction

The stagnating improvement in processing speed and the increasing availability of multi- and many-core processors have led to a growing interest in methods and tools to ease concurrent and parallel programming. Transactional Memory (TM) is considered as a promising candidate to replace traditional mutual exclusion in critical sections by more intelligent concurrency control (CC) methods. TM eliminates deadlocks and generally improves the scalability on multi-core machines allowing more concurrency in critical sections.

As the name suggests, TM provides transparent use of transactions on shared data in main memory. Transactions, as known from database or distributed systems, speculatively execute a set of instructions to be rolled back in case of data inconsistency or deadlock. A rollback consists of aborting the execution, a discard of all modifications and a restart at the beginning.

Especially when performing dirty reads there is a critical time period between the occurrence of a data inconsistency and its detection. In this period the transaction works on inconsistent data and may run in multiple different problems: Pointers can be invalid, expressions in conditional branches may have wrong results and lead to endless loops or parameters to operating system resource allocations (such as memory allocation) may be too big, resulting in resource exhaustion. Transactions which run in such problems are known as
doomed transactions and opacity is the property of TM systems to hide the side effects of doomed transactions.

Incremental validation is a known method to achieve opacity in TM systems written in software (Software Transactional Memory, STM). Accordingly, on each read of data a transaction validates all its previously read data by a comparison of a formerly taken copy to the current state of the data in memory. This method is save in regards to modifications in memory, but not in respect to memory reclamation (freeing memory) which can cause unexpected memory access violations in transactions and process termination as its consequence.

Hudson et al. presented an algorithm for memory management (memory allocator) for STM which prevents the occurrence of segmentation faults caused by inconsistencies in doomed transactions. Main concept of the allocator is to buffer and defer reclamations of memory blocks and perform them when no transaction exists which could eventually try to access the affected memory blocks.

Obviously, deferring memory reclamation has some disadvantages such as increased memory consumption. Thus, we have analyzed the side effects of this method and possible solutions to reduce or prevent them. Based on this knowledge we have developed a different method, which significantly reduces memory consumption and slightly improves the response time of the allocator functions (allocation and reclamation). The results have been evaluated by comparison using benchmarks such as the Stanford Transactional Applications for Multi-Processing (STAMP).

The following section will give a brief introduction in the problem of opacity in TM and existing solutions (Section 2). Section 3 then discusses the memory allocator of Hudson et al. and its side effects. In Section 4 the design of our method is explained and in Section 5 the evaluation and results are presented. In the end we give a short conclusion and prospective on future work.

2 Opacity in Software Transactional Memory

Explaining doomed transactions and opacity requires at least a simplified model of transactions in STM: In a TM-enabled application certain critical code sections are marked to be executed as a transaction by the currently active thread. Those sections are typically instrumented with calls into the STM runtime library, which enforces the concurrency control. A transaction performs an atomic transformation of shared data from one consistent state into another. Thus, the shared data is inconsistent if at least one transaction started to update shared data and has not yet finished. In turn, the state of a transaction is said to be valid if all data read by it (its read-set) originates from exactly one consistent state.

Currently, the most efficient STM implementations are based on optimistic concurrency control algorithms. Transactions are executed speculatively assuming that there are no concurrent transactions in the first place. Thus, those transactions will inevitably run into inconsistent states that are meant to be
detected and solved later by a rollback. During the time period between occurrence and detection the transaction works on inconsistent data and produces unexpected side effects. While some side effects are of minor relevance others can crash the application and even the entire operating system. A TM system guarantees opacity if it hides all these side effects.

This is an extended list of possible side effects originating from [2]:

- Runtime errors
  - Segmentation faults, caused by erroneous pointers
  - Arithmetic faults, caused by erroneous operands (such as null divisor)
  - Illegal instruction faults, caused by erroneous code modifications (considering self modifying code) or call or jump targets
- Bypassing concurrency control due to erroneous call or jump targets
  - Execution of non-transactional code
  - Exit without commit
- Non-terminating code, caused by invalid values in branch or abort conditions
  - Infinite loops
  - Infinite recursions
- Resource exhaustion, caused by invalid parameters to resource allocation functions, such as memory allocation

While the reason for most of the errors above arise directly from the value received by a dirty read others occur as a consecutive error to unintended modifications to data on the stack (e.g. when crossing the boundaries of a local array). Most error prone are stack pointer (SP) and base pointer (BP) which are used to access local data via an offset and the return address which points to the instruction to return to from the current function. As soon as SP or BP gets invalid, every access to local data is invalid as well which leads to any of the errors above.

There are mainly three different approaches to prevent those errors which will be explained in the following sub-sections.

2.1 Mutual Exclusion

The easiest way to provide opacity is to use locks to guarantee mutual exclusion on shared data according to a pessimistic concurrency control approach. Thus, dirty reads are forbidden per definition and doomed transactions cannot occur. But use of locks in TM has several disadvantages:

- In native programming languages such as C locks have to be associated with memory blocks of certain size (granularity). Lacking alternatives, locks have to be stored in a global table separated from the memory blocks. Entries in this table are called owner records (orecs), because they were originally introduced to store ownership of objects. Thus, each access to a memory 'object' requires an additional access to the orec which in turn increases cache miss rate on hardware level and thereby reduces scalability of the TM.
Locking protocols involve waiting time which is in some cases just wasted. Consider a transaction \( A \) which waits on a lock held by transaction \( B \). Transaction \( B \) runs in a deadlock and performs a rollback, thereby releasing the lock. Thus, \( A \) has been waiting for nothing. Additionally, those wait-for relationships are transitive, which means, another transaction may have been waiting for \( A \) as well and the case can occur again after rollback. Considering at least one transaction to successfully finish in a conflicting situation the worst case waiting time for the single transaction still grows quadratically with the number of active transactions.

Increasing the granularity of memory objects associated with locks reduces the probability of conflicts, cache misses and waiting time in turn but it reduces the concurrency and scalability as well.

Another method to reduce the waiting time is to allow so-called lock stealing, where a transaction may decide to steal the lock currently held by another transaction and proceeds with its work without waiting (cf. [3]). But this eliminates the guaranteed mutual exclusion and again requires strategies to deal with doomed transactions as applied for optimistic concurrency control mechanisms explained in the next sections.

2.2 Sandboxing

A way to achieve opacity in optimistic concurrency control is to embed transactions in a sandbox which prevents some errors of doomed transactions and transparently handles the remaining errors. This approach is almost similar to the execution of intermediate code in a java virtual machine or a common language runtime.

The most comprehensive existing example for sandboxing in C has been published by Dalessandro and Scott [2]. They applied sandboxing on an STM implementation which uses oreo-based validation and deferred updates. That means in particular, that every write access to any application data is just stored in a local log (so-called write-set or redo-log) of the transaction. The actual write to the shared data is performed after the transaction has been checked to be valid at commit time.

The proposed sandbox additionally provides the following mechanisms to guarantee opacity of transactions:

- Catching runtime errors in signal handlers which validate and abort the transaction in case of inconsistency.
- Timer triggered repeated validation to escape from endless loops or recursions.
- Validation prior to the execution of indirect jumps or function calls inside transactions to prevent bypassing of the CC mechanism.
- Validation of the parameters to memory allocation functions to prevent memory exhaustion.
- Validation of potential access to SP.
Hence, besides the deferred update for any data, the main method applied to achieve opacity is to insert validation at critical points in the transactional section by instrumentation. Sandboxing is said to cause more latency but Dallessandro and Scott have shown good performance and scalability of their approach at least with the benchmarks they have used. Others criticize sandboxing for potentially overriding signal handlers of the application but this can be solved by chaining the signal handlers as it was illustrated in their work as well.

2.3 Incremental Validation

A widely accepted method to ensure opacity is incremental validation as proposed in [1]. The fundamental principal here is to validate the whole read-set on each read (cf. Listing 1.1). Thus, a validation consists of a validation of every entry in the read-set on each consecutive read. This validation can be performed according to two methods:

1. value-based: The read-set contains the value first read by the transaction which is compared against the current content of the originating location in memory. Differences indicate inconsistency (see for example NOrec [4]).

2. oreo-based: The read-set contains the value and the state of the oreo seen on the first read access. The oreo state might be represented by a version number for example, which is incremented on each write access to the associated location in memory. In case of lock stealing, the oreo will contain the current value of the lock (e.g. lock owner, see for example SkySTM [3]). Instead of accessing the originating location in memory this method just validates against the state of the associated oreo comparing either the version number or lock state. Version differences or lost locks indicate inconsistencies in this case.

Due to the repeated validation of the whole read-set on each transactional read, the runtime complexity of incremental validation rises quadratically with the number of reads. The average effort can be reduced using for example a global commit counter, which is incremented with each commit of transactions. Thus, a transaction can skip validations as long as the commit counter has not been incremented. But the worst case complexity of this method is still quadratically rising with the number of reads considering enough concurrent transactions. Another issue of a global commit counter or oreo-based validation is that they
cannot deal with concurrent modifications on shared data by concurrent threads which do not run in a transaction because they simply ignore this mechanisms. Thus, the developer has to make sure that those cases will not occur.

Considering the runtime complexity there is a trade-off between sandboxing and incremental validation. While incremental validation applies to each read of shared data sandboxing validates critical instructions only, but the amount of critical instructions can be higher then the amount of shared reads. Thus, both approaches have to be further analysed in future work and maybe combined to cover both cases.

3 Quiescence for Memory Reclamations

A remaining problem of incremental validation arises through memory reclamation (freeing memory) in transactions. Those STMs that support memory management in transactions generally implement the following basic algorithm:

- Memory allocations are performed directly and stored in a log simultaneously. In case of a rollback all the logged memory allocations have to be returned to the memory management (i.e. freed).
- Memory reclamation just get stored in a log. They will be executed if the transaction commits or they will be discarded if the transaction rolls back.

Considering properly implemented concurrent applications a memory block (or references on it) will be privatized before it gets freed. That means, that a shared pointer referencing this memory block will be altered to indicate that it is no longer valid. This might be achieved by assigning NULL to the pointer (see Listing 1.2) or removing it from a list for example. Before accessing the data other threads must test the reference first (see for example Listing 1.3). A thread, which does not follow this protocol will inevitably run into a segmentation fault when the associated memory is freed. Thus, we do not need to consider applications which do not perform a privatization prior to a reclamation of a shared memory block.

A transaction trying to access a probably privatized pointer is depicted in Listing 1.3. In Line 2 the transaction reads and validates the shared pointer (shared_ptr) which is probably privatized using the function in Listing 1.1. In Line 3 it makes sure that the pointer is not privatized before it accesses the referenced memory location in Line 4.

| Line | Code                                      | Description                         |
|------|-------------------------------------------|-------------------------------------|
| 1    | /* privatize ptr */                       |                                     |
| 2    | void* local_ptr = shared_ptr;             | setting the local pointer to the shared pointer |
| 3    | shared_ptr = NULL;                        | setting the shared pointer to NULL |
| 4    |                                          |                                     |
| 5    | /* reclamation */                         |                                     |
| 6    | free(local_ptr);                          | freeing the local pointer          |

Listing 1.2. Example of privatization
The following cases may occur in respect to memory reclamations:

1. The pointer on a memory block is privatized and freed in a transaction.
2. The pointer on a memory block is privatized in the transaction but freed afterwards without running a transaction.
3. The pointer on a memory block is privatized and freed without running a transaction.

Even with incremental validation the first two cases already cause a problem: After the last validation of the transaction (line 2 in Listing 1.1) and the actual access to the memory location (Line 3 in Listing 1.1) the privatizing transaction could perform its commit and free the memory. Thus, the accessing transaction will receive a segmentation fault (SkySTM for example suffers this problem in case of lock stealing). This can be prevented using a global lock to establish mutual exclusion between concurrent commits and reads. But this would heavily decrease the concurrency proportional to the number of reads during transaction execution.

A method which solves the privatization problem without mutual exclusion is called quiescence mechanism \[6\]. The general idea is to defer access to privatized data until every active transaction has noticed the privatization. One implementation of this concept is to perform the privatization and then block the privatizing transaction before it modifies the privatized data until every concurrent transaction has either committed or aborted. Thus, all remaining active transactions will read the new value of the privatized data (pointer in our case). That means, there is a time when quiescence on that privatized data has been achieved and the privatizing transaction can safely proceed (free the associated memory in our case). Disadvantage of this method is, that it involves waiting for other transactions which might be of arbitrary duration.

In case of incremental validation the described problem arises from memory reclamations only. All the other data inconsistencies in respect to privatizations will be detected through the validation after the dirty read (i.e. in Line 4 of Listing 1.1). Thus, it is enough to defer just memory reclamations to a time of quiescence. This is for example implemented in NOrec as a so-called epoch-based memory reclamation \[7,8\]: The execution time of a concurrent application gets logically partitioned into so-called global epochs. The first global epoch begins at the start of the application. The lifetime of each thread is partitioned in thread-specific epochs as well. A new epoch of a thread begins with the start

```
transaction {
    int* ptr = txread(shared_ptr);
    if (ptr != NULL) {
        int val = txread(*ptr);
        /* ... */
    }
}
```

**Listing 1.3.** Transaction accessing the privatized pointer ptr
of the thread and every start, restart and end of a transaction. A new global epoch begins each time when all threads have switched into a new thread-specific epoch. Every memory reclamation request in transactions gets associated with the currently running global epoch and stored in a global data structure called limbo. The limbo is checked by each committing transaction for reclamation requests that have reached the point of quiescence (older than two global epochs). Those requests will then be executed by the currently committing transaction.

```c
/* privatize_ptr */
void* tmp = ptr;
ptr = NULL;

/* transaction-aware barrier */
transaction { /* intentionally empty */ }

/* reclamation */
free(tmp);
```

Listing 1.4. Privatization 'without' transaction

The third case listed above generally requires to manually apply the quiescence mechanism in some way. For example a barrier between privatization and memory reclamation which is interoperable with the CC used in other threads accessing the memory block. This barrier might be to temporarily acquire a lock in case of mutual exclusion or run an empty transaction in case of STM (cf. Listing 1.4). In other words: the developer is responsible for the correct outcome of the privatization when performed without a CC mechanism.

The epoch-based memory reclamation still has some disadvantages:

**Impact on Memory Reclamation in General:** Memory reclamations outside of transactions usually do not consider the quiescence mechanism. Thus, the second case described above is not covered and can still cause memory access violations. Only the instrumentation of all memory reclamations even those outside of any critical section would solve this problem. This is technically possible but it has a negative impact on the performance of the whole application.

**Increased Memory Consumption:** Deferring memory reclamation obviously causes higher memory consumption as known from garbage collection (GC) systems in managed code environments. Those systems generally know at each time whether references on certain memory blocks still exist or not. Thus, GC could release the free memory if required. In contrast the epoch-based memory reclamation cannot release all vacant memory at any point in time. Thus, besides the fact that it causes higher memory consumption in general, it will not be able to solve out of memory situations even if vacant memory is available in the limbo.
4 Incremental Validation without Quiescence

Incremental validation is a simple method to guarantee opacity except for memory access violations due to concurrent reclaims. Because of the disadvantages of epoch-based reclamation we developed another method which combines incremental validation with an element of sandboxing to solve the memory access violations. We have chosen NOrec as the basis for our STM prototype to allow a direct comparison to epoch-based memory reclamation. NOrec uses deferred updates, incremental validation optimized by a commit counter and epoch-based memory reclamation. Modifications to NOrec mainly affect the memory management and an enhancement to handle segmentation faults:

**Allocator:** Our simplified allocator replaces the epoch-based memory reclamation. It implements the basic memory management algorithm for transactions explained in the beginning of Section 3: Allocation and reclamation requests are logged. The log is discarded on each rollback. Allocation requests get executed instantly and freed in rollbacks. Reclamation requests from the log are executed on commit.

**Handling Memory Access Violations:** A signal handler has been introduced to deal with segmentation faults. Default behavior of a segmentation fault of an application is a process termination. Therefore, we optimized the case where the handler is not called upon an application error: If the handler is called inside an active transaction and the commit counter indicates a modification since we have last validated, we first consider a conflict as the reason and instantly perform a rollback. If there was really a conflict the transaction will probably succeed in its next try. If there was no conflict the transaction will receive the segmentation fault again but this time the commit counter is eventually not modified which indicates a valid read-set and thus an error of the application. In the latter case the error is escalated and the application error gets visible.

This method implicitly solves even the cases where the reclamation request occurs outside of a transaction (cf. Section 3).

We did not implement chaining of signal handlers for our prototype but it just requires to override the runtime library functions to install signal handlers (e.g. `signal` and `sigaction`). Those have to be modified to keep our signal handler in front of the chain and the signal handler has to call the next signal handler in the chain or terminate the process to escalate signals.

5 Evaluation

A comparison of NOrec with our modified version NOrecSig allows an evaluation of the runtime performance in terms of scalability on parallelization and memory consumption by measurements. For orientation purposes a third STM implementation called CGL has been measured which establishes mutual exclusion between all critical sections (i.e. transactions) using a single global lock. Differences between CGL and STM algorithms are known and not discussed here.
We have selected those benchmarks of the Stanford Transactional Applications for Multi-Processing (STAMP, [9]) which contain memory reclamations in transactions (except yada which had a bug in our version). To demonstrate worst case behavior we implemented another benchmark called opacity which aggressively repeats concurrent memory allocations and reclamations.

intruder: Simulated intrusion detection system processing different attacks.

ssca2: A benchmark operating on a huge directed multi-graph which concurrently adds and removes nodes.

vacation: Simulation of a reservation system for resources such as flights, rooms etc. with configurable amount of clients.

opacity: Mimics an application with multiple threads rapidly exchanging messages via a shared message queue.

Measurements ran on a multi-core machine with four 3GHz AMD Opteron 6282SE processors, with 16 Bulldozer Cores each, a 128GB main memory, Debian Linux with Kernel 2.6.32-5 and a GCC 4.4.5. The number of threads has been increased up to 32. Measurements have been repeated until a confidence interval of 5% of the interval \([\text{min}, \text{max}]\) at a confidence level of 95% has been reached. Graphics with redundant information have been removed to reduce the length of this section.

![Fig. 1. intruder: Exec. time [ms]](image1)

![Fig. 2. vacation: Exec. time [ms]](image2)

The execution time for both implementations was in all our observations almost similar with a slight advantage of the NOrecSig variant (cf. Figures 1 and 2, execution time in milliseconds).

The memory consumption has been evaluated by detailed observation of the current heap size at any time of execution \((m(t))\). The maximum total size of the heap \((m(t_{\text{max}}))\) has been determined and an average memory consumption \(\overline{M}\) has been calculated as the integral of the current memory consumption \(m(t)\) over the time of execution normalized by execution time.

\[
\overline{M} = \int_{t_{\text{start}}}^{t_{\text{end}}} \frac{m(t)}{t_{\text{end}} - t_{\text{start}}} \, dt \quad [\text{byte}] 
\]
Memory consumption of NOrecSig was in most cases significantly lower and in some cases even similar. The worst case in maximum and average was reached with our benchmark (Figures 3 and 4). The difference of 1.2TB in maximum memory consumption illustrates the danger of resource exhaustion. The intruder benchmark (Figures 5 and 6) shows another case where maximum and average memory consumption of NOrec are just moderately higher than that of NOrecSig.

6 Conclusion

The review of techniques to deal with memory access violations of doomed transactions due to memory reclamation after privatization revealed remaining issues with incremental validation and epoch-based memory reclamation. Inspired by sandboxing, the approach proposed here is to use incremental validation and

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Memory is not accessed and thus can grow over the actual capacity of the hardware
handle generated segmentation fault signals to recover from inconsistent states of the transaction. This method solves all memory access violations occurring from memory reclamations inside and outside of transactions. A comparison of a prototype to NOrec has proven, that it slightly improves the response time of memory management functions and effectively decreases memory consumption. That way it improves the opacity of incremental validation because it prevents unexpected memory exhaustion to occur. A future comparison to sandboxing will clarify their relationship in terms of throughput and scalability.

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