Abstract of "Debugging and Profiling of Transactional Programs" by Yossi Lev, Ph.D., Brown University, May 2010.

Transactional memory (TM) has become increasingly popular in recent years as a promising programming paradigm for writing correct and scalable concurrent programs. Despite its popularity, there has been very little work on how to debug and profile transactional programs. This dissertation addresses this situation by exploring the debugging and profiling needs of transactional programs, explaining how the tools should change to support these needs, and describing a preliminary implementation of infrastructure to support this change.

Debugging and Profiling of Transactional Programs

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Chapter 1

Introduction

This dissertation discusses the topic of debugging and profiling of transactional programs: that is, programs that use transactional memory (TM) for concurrency control. Transactional memory has become increasingly popular in recent years as a promising programming paradigm for writing correct and scalable concurrent programs. Despite its popularity, and the availability of several STM runtimes and compilers for transactional programs that use them, there has been very little work on how transactional programs can be debugged and profiled. This dissertation addresses this situation by exploring the debugging and performance profiling needs of transactional programs, explaining how the tools can change to support these needs, and implementing preliminary infrastructure to support this change.

1.1 Background

In concurrent software it is often important to guarantee that one thread cannot observe partial results of an operation being executed by another thread. These guarantees are necessary for practical and productive software development because, without them, it is extremely difficult to reason about the interactions of concurrent threads. In today's software practice, these guarantees are almost always provided by using locks to prevent other threads from accessing the data affected by an ongoing operation. Such use of locks gives rise to a number of well known problems, both in terms of software engineering and in terms of performance.

When using locks, it is the programmer's responsibility to follow the locking convention, making sure that the right set of locks are held when accessing a data item, while avoiding problems such as deadlocks and livelocks. Doing so by using a single lock to protect all shared data may not be difficult, but the resulting program will often not scale well, because accesses to all shared data will be serialized by that lock. On the other hand, using a more fine grained locking scheme may improve the program's scalability, but will often result in more complex, error-prone code that is more difficult to maintain.

Another problem with code that uses locks is that it does not compose well. When methods use locks to protect the data that they access, it is often impossible to build a new method using an existing one without understanding how the existing method is implemented. As an example, consider having a `deposit` and `withdraw` methods, that update the balance of a bank account. The update to the account's balance by these methods is done *atomically*, as if it is executed with no interference from other threads. In other words, each method guarantees, for example by holding a lock, that no other thread is updating balance between the time it reads balance, and the time it writes it with the new value; without this guarantee, updates to balance by the other threads might be lost.

Suppose now that we would now like to implement a new `transfer` method that atomically moves money from one account to another. If `deposit` and `withdraw` protect the accounts they operate on using locks, and the new `transfer` method simply calls `withdraw` and then `deposit` to make the transfer, then another thread executing in between these calls may notice, for example, that the total amount in the two accounts has changed, which may lead to an erroneous behavior. Instead, to guarantee the atomicity of the `transfer` operation, the new method has to know which locks are used to protect the accounts, and acquire them *prior* to executing the `deposit` and `withdraw` operations. Moreover, the locks must be acquired in a particular order to avoid deadlocks that may occur, for example, if a transfer from account A to account B is executed concurrently with a transfer from account B to account A. The need of the caller method to know how each of the methods that it calls is implemented is a severe problem in terms of software engineering, as it often leads to code that is very difficult to design and maintain.

Transactional memory (TM) tries to address these problems by allowing the programmer to specify *what* should be executed atomicity, without specifying *how* the atomicity should be achieved. In particular, TM allows the programmer to specify code regions in *atomic blocks*, and the TM runtime guarantees that each execution of such a code region seems to be atomic, as if multiple memory locations can be accessed and/or modified in a single atomic step. Thus, TM relieves the programmer from the burden of following a locking convention to protect the shared data these code regions access: it is the TM runtime's responsibility to guarantee the atomicity, and to avoid deadlocks, livelocks and other problems that may arise in the process. Transferring the responsibility for atomicity to the TM runtime also addresses the lack of composability of lock-based programs, as the programmer no longer needs to understand how the atomicity of an existing method is implemented when using it to build a new atomic operation.

To guarantee atomicity, the TM runtime executes all the memory accesses of an atomic block in a *transaction*. A transaction may *commit* successfully, in which case all of its memory accesses take effect atomically together at a *commit point*; otherwise the transaction *aborts*, and none of its accesses become visible to other threads. When a transaction aborts, the TM runtime can retry executing the atomic block using additional transactions, until one commits successfully.

Transactions execute *atomically* and in *isolation*, implying that a transaction never sees a partial execution of another, and that it always operates on a consistent view of the memory. Thus, a transaction is typically aborted if a location that it read is modified before it tries to commit. The ability to abort transactions allows the TM runtime to use an optimistic approach when running them: two transactions can be run in parallel, and if the two conflict on a shared resource then one can be aborted.

TM runtimes can be implemented in hardware (HTM) [13], with the hardware directly ensuring that a transaction is atomic, or in software (STM) [33] that provides the “illusion” that the transaction is atomic, even though it is in fact executed in smaller atomic steps by the underlying hardware. HTM runtimes are expected to run transactions with significantly less overhead than STM runtimes; on the other hand, most practical HTM proposals impose various limitations on the code that a hardware transaction can execute (and still commit successfully). For this reason, some TM runtimes use a hybrid approach [5, 24, 19], where a transaction is first tried using an HTM (if available), and if that fails, it is executed using an STM. Such TM runtimes can take advantage of *best-effort* HTM solutions [5, 25], when available, to boost the performance of an otherwise software only solution.

1.2 Debugging and Profiling Transactional Programs

While TM promises to substantially simplify the development of correct concurrent programs, programmers will still need to debug code while it is under development, and therefore it is crucial that we develop robust TM-compatible debugging mechanisms. In this dissertation we focus on providing debugging support for programs that use an STM runtime, but also explore how the debugging functionality could be made to work in a hybrid environment where some transactions may execute using HTM.

Providing debugging support for transactional programs is challenging. One of the most important features that debuggers provide when stopping a program is the ability to view the program’s memory and variables from the point of view of the debugged program, or more precisely, of a particular thread. This simple functionality does not follow automatically to transactional programs. In particular, recall that an STM runtime only provides the “illusion” of atomicity, while in fact the transaction's memory accesses are executed by a series of smaller atomic steps. If we were using a regular debugger to inspect variables of a program that uses an STM runtime, the debugger would break the illusion, confusing the user with runtime artifacts unrelated to the program being debugged. Thus, for the debugger to provide the user with the values as seen by the transactional program, it must interoperate with the STM runtime to provide the necessary isolation and atomicity guarantees with respect to inspected data.

Another issue the debugger must be aware of is the different control flow of transactional programs. Recall that a transaction executing an atomic block may be aborted, in which case the TM runtime may retry the execution using another transaction. If the debugger is used to step an execution of an atomic block, and the transaction being stepped is aborted, retrying would result in unexpected control flow that is unexplained by the user code. In particular, control will be transferred to the beginning of the atomic block, which may be in another function or another file than the code in which the user was stepping. Debuggers should therefore try to prevent such scenarios (for example by telling the TM runtime that a transaction is being stepped), or at least provide the user with an appropriate explanation when they occur.

In addition to debugging support for transactional programs, there is also a need for profiling tools that will help programmers understand and improve the performance of their programs. While having TM be responsible for synchronizing accesses to shared data significantly simplifies the task of writing correct, concurrent programs, it also hides information from the programmer that may be crucial for performance profiling. In particular, because programmers are no longer aware of which synchronization mechanism protects what data, it is challenging for them to detect performance bottlenecks involving these mechanisms. The profiler should thus work with the TM runtime to detect such bottlenecks, and present them to the programmer in a meaningful way.

Despite the need to adjust debugging and profiling tools for transactional programs, we claim that with specialized tools, debugging and profiling of transactional programs would be *easier* than debugging concurrent programs today. There are several reasons for that.

First, one of the main reasons that debugging concurrent programs is difficult is that the user can no longer describe data structures using simple, sequential invariants, and methods using pre and post conditions. Consider the problem of debugging a complex data structure, such as a red-black tree. In a quiescent state, where no method is executing, the tree satisfies various invariants governing how it is balanced. To debug a sequential tree implementation, one should check that the tree satisfies its invariant when each method is called, and again when the method returns. Naturally, a method in progress may temporarily violate the tree's invariants.

When debugging a concurrent lock-based programs, these principles evaporate. A method call rotating a subtree may cause keys temporarily to disappear, or to be duplicated, or the tree to become temporarily unbalanced. In programs based on fine-grained locking, some critical section may always be in progress, and the tree may *never* be entirely consistent. Halting the program while some threads are in a critical section could reveal such anomalies, making it difficult to understand whether the tree implementation is correct. There are too many interleavings to distinguish good states from bad.

When debugging concurrent transactional programs, we can reclaim the sequential invariants. Recall that transactions execute in isolation, implying that no transaction can observe another's partial effects. As long as the debugger preserves the isolation properties of the TM runtime, the user should never see the partial effects of any transaction other than the one being debugged. Each transaction "sees" a quiescent tree when it starts, and the user can check that observed departures from the tree invariant are due to the partial effects of the transaction being debugged.

Transactional debugging has other, perhaps less-obvious advantages. Today, when a user stops a thread at a breakpoint and steps over a function call, the Sun Studio dbx debugger [36] lets all other threads run while the debugged thread is executing this step. Clearly, this policy makes reasoning about program behavior more difficult, but it was found necessary to avoid deadlocks that could arise if the function were to wait on a condition variable signaled by a concurrent thread. By contrast, when debugging transactional code, there is no need for such a policy. If the underlying TM is obstruction-free (for example, DSTM [16]), then a single-stepped transaction will always succeed when run in isolation. Otherwise, the debugger can sometimes take advantage of the underlying TM system to find out which transaction is blocking the debugged thread, and allow the user to either abort it or step it to completion. Finally, if there is no way for the stepped transaction to win the conflict, it can always be aborted. These choices are not available when the programmer is the one responsible for the synchronization between the threads (for example by using locks).

Another advantage of the transactional model is that TM runtimes inherently track a lot of information useful for debugging, such as transaction read and write sets, tentative versus committed values, data conflicts, and who is waiting for whom. The debugger can present this data to the user, or even use it internally, for example to notify the user with the reason of why a stepped transaction was aborted.

Finally, transactional programming provides a great opportunity for profiling. Because of the optimistic nature of transactions, the TM runtime keeps track of conflicts in a much finer granularity than that of the atomic blocks in the program. Thus, the programmer can begin with a *simple and correct* program that uses coarse grained atomicity, and successively refine it based on information about individual conflicts in the atomic blocks of the program, and the cost that they incur. A good profiling tool can help the programmer identify the atomic blocks that are most likely to benefit from refinement. Furthermore, as we show, the information collected by the TM runtime can be used to *replay* an execution of any individual transaction, so the profiler can present the user with the step-by-step execution of costly transactions.

1.3 Outline

In this work we explore the debugging and profiling needs of transactional programs, describe how debuggers and TM runtimes could be changed to provide them, and develop initial infrastructure to support this change. Our work focuses on providing debugging and profiling support with STM runtimes, but also describes how some of the features may be supported in a hybrid TM environment. The document is organized as follows.

In Chapter 2, we explore the high level ideas behind debugging of transactional programs. We describe the debugging features that we believe will be useful when debugging transactional programs, and explain how the debugger and the TM runtime can work together to support them. We show that the TM infrastructure can be exploited to support all "standard" debugging capabilities that are supported today for regular programs, as well as some new, powerful debugging features.

In Chapter 3, we focus on how transactional debugging features can be implemented in a real, commercial debugger, which may need to support programs that use different TM runtimes, with different STM algorithms. We describe the development of the tm_db library, an external library that helps debuggers provide some of the debugging features discussed in Chapter 2. The tm_db library provides the debugger with an interface for transactional debugging that fits well with most STM algorithms that are in use today, thereby abstracting away the implementation details of the particular TM runtime used by the debugged program. The library was recently integrated with a preliminary transactional debugging extension of the Sun Studio dbx debugger. The chapter describes the library's functionality and the rationale for its design; in addition, it provides guidelines for how to design TM runtimes to improve the debugability of the code that uses them.

In Chapter 4 we change the focus to profiling of transactional programs. We present T-PASS, a prototype profiling system that we developed for this purpose. We describe the information T-PASS provides, how it is presented to the user, and provide examples of how this information may be useful when optimizing transactional programs both in a software only and in a hybrid TM environments. In addition, we show how the debugger and the profiler can be combined to provide additional information on performance bottlenecks, for example by replaying transactions that were executed for longer than a certain period of time.

Finally, Chapter 5 includes concluding remarks, and directions for future work.

1.4 Related Work

Lev and Moir [23] were the first to address the topic of debugging transactional programs. In their work, on which Chapter 2 is based, they explore what debugging capabilities are required for transactional programs, and how debuggers can be changed to support them. Herlihy and Lev [15] then built on top of this work and developed the tm_db library, to provide commercial debuggers with the infrastructure to support transactional debugging with various STM algorithms. This work is presented in Chapter 3. To support profiling of transactional programs, Herlihy and Lev introduced T-PASS [14], a prototype profiling system that we present in Chapter 4.

Despite the popularity TM has recently gained, we are aware of only very little other work on debugging and profiling of transactional programs. Harmanci et al. [11] presented TMUnit, a system to debug and optimize TM runtimes. Similar to tm_db, TMUnit can be used with different STM algorithms, but its focus is on debugging and testing the TM runtimes and not the transactional programs that use them. More recently, Zyulkyarov et al. [37] presented a debugging extension for the WinDbg debugger, developed simultaneously with tm_db, to support debugging of transactional programs that use the Bartok-STM runtime [12]. Their solution supports many of the debugging features tm_db supports, as well as the ability to detect conflicting accesses in the program. Despite the similarities in the supported functionality, the design principles of the two solutions are quite different because tm_db is designed to work with a variety of debuggers and STM runtimes, and hence makes less assumptions about the debugging environment in which it is used (e.g. tm_db does not assume that the debugger process can call functions in the debugged process space, or automatically step threads out of an atomic block to avoid conflicts with the debugged thread). Finally, debugging and profiling support for the TCC HTM system [10] and its ATLAS simulator [27] was proposed [28, 3]. While these tools provide a wide range of debugging and profiling support, they are specialized for one particular HTM implementation, and require additional hardware. Moreover, because the TCC solution never runs transactions in software, much of the profiling information that is relevant when using an STM or an HyTM runtime is not provided.

Chapter 2

Debugging Transactional Programs

In this chapter we take a first look at the question of how transactional programs can be debugged. We show how basic debugging features, like placing breakpoints, stepping through the program code, and viewing and modifying data, could be adjusted for transactional programs. In addition, we believe that the different nature of transactional programs will give rise to new debugging techniques, requiring additional debugging mechanisms. We present several such mechanisms, and describe how we can use the transactional memory infrastructure to support them. Our description focuses on how to enable debugging in software and hyrbid software-hardware transactional memory systems.

2.1 Introduction

In this chapter we explore the question of which debugging capabilities transactional programs may require, and how debuggers can provide them.

We begin by addressing the question of how basic debugging features that are supported for regular programs should be adjusted for transactional programs. Like with regular programs, users will need to place breakpoints and step a transactional program. But how do we stop and step an execution of an atomic block? If the execution consists of a series of transactions, only the last of which is successful, do we stop in *each* of these transactions, or only in these that may still commit successfully? If we step a transaction and it is then aborted due to a conflict, how do we expose this special flow control to the user? Can we avoid these aborts by giving the stepped transaction a higher priority over its rivals when resolving conflicts?

Similarly, the user may want to stop when a particular variable is written (or read), by placing a *watchpoint* on that variable. In this case, should the debugger stop whenever a transaction accesses the variable for writing, or only when one successfully commits a change to it?

Another fundamental debugging feature is the ability to view and modify data. As described in Chapter 1, transactional memory only provides the programmer with the *illusion* of atomicity, while in practice variables may be updated one at a time. For debuggers to interact with a transactional program in a meaningful way, they will have to maintain this illusion, displaying the data as seen by the debugged program (or more precisely, by the thread to which the debugger is attached). We explore how debuggers can work alone with the TM runtime to provide users with a meaningful view of the data.

In addition to adjusting the basic debugging features for transactional programs, the different nature of transactional programs may encourage different kinds of debugging, which will give rise to additional, more powerful debugging features. One of the key advantages of using transactions is that they seem to be executed in isolation, with no interference from other transactions. This property allows the user to reason about atomic blocks in terms of pre and post conditions, thinking about the effect of an atomic block as a whole, and verifying that none breaks any of the system's invariants.

For this reason, a user may want to begin debugging in an inter atomic-block level, and only step an execution of an atomic block that violates a system invariant. We present two new debugging features to support this. The first allows the user to place a breakpoint on a statement inside an atomic block, but to stop only if and when a transaction that executes this statement commits; the second allows the user to replay the execution of such a transaction.

One of the key observations of this work is that the debugger can take advantage of the TM runtime infrastructure to provide many of the debugging features with much lower overhead than would be required for regular programs. We focus on the algorithms to provide the debugging features with an STM runtime, but also explore how and which of these features can be provided in a hybrid transactional memory (HyTM) system, where an execution of an atomic block may be tried first using hardware transactions, and only if failed will be executed using software transactions. For concreteness we describe the debugging techniques in the context of the word-based HyTM system of Damron et. al. [5].

The rest of this chapter is organized as follows. In Section 2.2 we provide a brief overview of the HyTM system of Damron et. at. [5]. In Section 2.3, we introduce some basic debugging modes and terminology that will be used throughout this chapter. In Section 2.4 we describe the various debugging techniques, and we summarize in Section 2.5.

2.2 A Word-Based HyTM Scheme

2.2.1 Overview

The HyTM system of Damron et. al. [5] comprises a compiler, a library for supporting transactions in software, and (optionally) HTM support. Programmers express blocks of code that should (appear to) be executed atomically in some language-specific notation [17]. The specific syntax that is used is not the point of this thesis; for concreteness, we assume the following simple notation:

```
atomic {
   ...
   code to be executed atomically
   ...
}
```

For each such atomic block, the compiler produces code to execute the code block atomically using transactional support. In particular, the produced code attempts to execute the block one or more times using HTM, and if that does not succeed, it repeatedly attempt to do so using the STM library.

The compiler also produces "glue" code that hides this retrying from the programmer, and invokes "contention management" mechanisms [16, 32] when necessary to facilitate progress. Such contention management mechanisms may be implemented, for example, using special methods in the HyTM software library. These methods may make decisions such as whether a transaction that encounters a potential conflict with a concurrent transaction should a) abort itself, b) abort the other transaction, or c) wait for a short time to give the other transaction an opportunity to complete. As we will see, debuggers may need to interact with contention control mechanisms to provide a meaningful experience for users.

Because the above-described approach may result in the concurrent execution of transactions in hardware and in software, we must ensure correct interaction of these transactions. The HyTM approach is to have the compiler emit additional code in the hardware transaction that looks up structures maintained by software transactions in order to detect any potential conflict. In case such a conflict is detected, the hardware transaction is aborted, and is subsequently retried, either in hardware or in software. Below we explain how software transactions provide the illusion of atomicity, and how hardware transactions are augmented to detect potential conflicts with software ones.

2.2.2 Transactional Execution

As a software transaction executes, it acquires "ownership" of each memory location that it accesses: exclusive ownership in the case of locations modified, and possibly shared ownership in the case of locations read but not modified. This ownership cannot be revoked while the owning transaction is in the `active` state: A second transaction that wishes to acquire exclusive ownership of a location already owned by the first transaction must first cause the owner transaction to abort. This can be done by the second transaction changing the status of the owner transaction to `aborted`, or by stealing ownership from the current owner, and requiring it to later `validate` its accesses and find out that it is no longer the owner of some of the locations it accessed, thus causing it to abort. Furthermore, a location can be modified only by a transaction that owns it. However, rather than modifying locations directly while executing, the transaction "buffers" its modifications in a "write set". If a transaction reaches its end without being aborted, it atomically switches its status from `active` to `committed`, thereby *logically* applying the changes in its write set to the respective memory locations it accessed.[1] Before releasing ownership of the modified locations, the transaction copies back the values from its write set to the respective memory locations so that subsequent transactions acquiring ownership of these locations see the new values.

2.2.3 Ownership

In the word-based HyTM scheme described here, there is an ownership record (henceforth *orec*) associated with each *transactional location* (i.e., each memory location that can be accessed by a transaction). To avoid the excessive space overhead that would result from dedicating one orec to

[1]If the STM algorithm allows a transaction's ownership to be stolen, then the transaction atomically verifies that it still has ownership of all locations it has accessed together with changing its status from active to committed.

each transactional location, we instead use a special *orec table*. Each transactional location maps to one orec in the orec table, but multiple locations can map to the same orec. To acquire ownership of a transactional location, a transaction acquires the corresponding orec in the orec table. The details of how ownership is represented and maintained are mostly irrelevant here. We do note, however, that the orec contains an indication of whether it is owned, and if so whether in "read" or "write" mode. These indications are the key to how hardware transactions are augmented to detect conflicts with software ones. For each memory access in an atomic block to be executed by a hardware transaction, the compiler emits additional code for the hardware transaction to lookup the corresponding orec and determine whether there is (potentially) a conflicting software transaction. If so, the hardware transaction simply aborts itself. By storing an indication of whether the orec is owned in read or write mode, we allow a hardware transaction to succeed even if it accesses one or more memory locations in common with one or more concurrent software transactions, provided none of the transactions modifies these locations.

2.2.4 Atomicity

As described above, the illusion of atomicity is provided by considering the reads and writes made by a transaction `T` to "logically" take effect atomically together at some point during its commit operation. In particular, it is guaranteed that at that *commit point*, all locations read by the transaction `T` have the values observed by `T`, and that any other transaction that takes effect after this point will see the effect of all `T`'s writes, as if they were all executed together in one atomic step. By preventing transactions from observing the values of transactional locations that they do not own, we hide the reality that the changes to these locations are in fact made one by one after the transaction's commit point. (Note that the transaction's commit point may not necessarily be the point its status is changed from `active` to `committed`, because with some implementations, at that point the locations the transaction has read may no longer contain the read values.)

If we use such an STM or HyTM package with a standard debugger, the debugger will not respect these ownership rules. Therefore, for example, it might display a pre-transaction value in one memory location and a post-transaction value in another location that is updated by the same transaction. This would “break” the illusion of atomicity, which would severely undermine the user’s ability to reason about the program. Therefore, we need to modify debuggers so they provide the user with the same atomicity illusion that TM provides the programmer with.

2.3 Debug Modes and Terminology

We distinguish between three basic debug modes:

- *Unsynchronized Debugging:* In this mode, when a thread stops (when hitting a breakpoint, for example), the rest of the threads keep running.
- *Synchronized Debugging:* if a thread stops the rest of the threads also stop with it. There are two synchronized debugging modes:
  - *Concurrent Stepping:* In this mode, when the user asks the debugger to run one step of a thread, the rest of the threads also run while this step is executed (and stop again when the step is completed, as this is a synchronized debugging mode).
  - *Isolated Stepping:* In this mode, when the user asks the debugger to run one step of a thread, only that thread’s step is executed.

For simplicity, we assume that the debugger is attached to only one thread at a time, which we denote as the *debugged thread*. If the debugged thread is in the middle of executing a transaction, we denote this transaction as the *debugged transaction*. When a thread stops at a breakpoint, it automatically becomes the debugged thread. Note that with the synchronized debugging modes, after hitting a breakpoint the user can choose to change the debugged thread, by switching to debug another thread.

2.4 Debugging Techniques

2.4.1 Breakpoints in Atomic Blocks

The ability to stop the execution of a program on a breakpoint and to run a thread step by step is a fundamental feature of any debugger. In a transactional program, a breakpoint will sometimes reside in an atomic block. In this section we describe a technique that enables the debugger to stop and step through such a block in the HyTM system, wherein an atomic block may have at least two implementations, for example, one that uses HTM and another that uses STM.

In keeping with the HyTM philosophy, we do not assume that any special debugging capability is provided by the HTM support. Therefore, if the user sets a breakpoint inside an atomic block, in order to debug that atomic block, we must *disable* the code path that attempts to execute this particular atomic block using HTM,[2] thereby forcing it to be executed using STM. If we cannot determine whether a given atomic block contains a breakpoint (for example, in the presence of indirect function calls), we can simply abort the executing hardware transaction when it reaches the breakpoint, eventually causing the atomic block to be executed by a software transaction.

One way to disable the HTM code path is to modify the code for the transaction so that it branches unconditionally to the software path, rather than attempting the hardware transaction. In HyTM schemes in which the decision about whether to try to execute a transaction in hardware or in software is made by a method in the software library, the code can be modified to omit this call and branch directly to the software path. An alternative approach is to provide the debugger with an interface to the software library so that it can instruct the software method to always choose the software path for a given atomic block.

In addition to disabling the hardware path, we must also enable the breakpoint in the software path. This is achieved mostly in the same way that breakpoints are achieved in standard debuggers. However, there are some issues to note.

[2]We do not want to disable *all* use of HTM in the program, because we wish to minimize the impact on program timing in order to avoid masking bugs.

```
atomic {
   v = node->next->value;
}

     ⟹

while(true) {
   tid = STM-begin-tran();
   tmp = STM-read(tid, &node);
   if (STM-Validate(tid)) {
      tmp = STM-read(tid, &(tmp->next));
      if (STM-Validate(tid)) {
         tmp2 = STM-read(tid, &(tmp->value));
         STM-write(tid, &v, tmp2);
      }
   }
   if (STM-commit-tran(tid)) break;
}
```

Figure 2.1: An example of an atomic block and its STM-based implementation.

First, the correspondence between the source code and the STM-based implementation of an atomic block differs from the usual correspondence between source and assembly code: the STM-based implementation uses the STM library functions for read and write operations in the block, and may also use other function calls to correctly manage the atomic block execution. For example, it is sometimes necessary to invoke the STM library method `STM-Validate` in order to verify that the transaction still holds ownership of all locations it has accessed, to ensure that all values read by the transaction so far represent a consistent state of the memory. Figure 2.1 illustrates the translation of a simple atomic block to its STM-based implementation (for brevity we present the generated code in `C`, although in practice the compiler directly generates assembly code).

The debug information generated by the compiler should reflect this special correspondence to support a meaningful debugging view to users. When the user is stepping in source-level mode, all of these details should be hidden, just as assembly-level instructions are hidden from the user when debugging in source-level mode with a standard debugger. However, when the user is stepping in assembly-level mode, all STM function calls are visible to the user, but should be regarded as atomic assembly operations: stepping into these functions should not be allowed.

Another issue is that control may return to the beginning of an atomic block if the transaction implementing it is aborted. Without special care, this may be confusing for the user: it will look like “a step backward”. In particular, in response to the user asking to execute a single step in the middle of an atomic block, control may be transferred to the beginning of the atomic block (which might reside in a different function or file). In such cases the debugger may prompt the user with a message indicating that the atomic block execution has been restarted due to an aborted transaction.

Finally, it might be desirable for the debugger to call `STM-Validate` right after it hits a breakpoint, to verify that the transaction can still commit successfully. This is because, with some HyTM implementations, a transaction might continue executing even after it has encountered a conflict that will prevent it from committing successfully. While the HyTM must prevent incorrect behavior (such as dereferencing a null pointer or dividing by zero) in such cases, it does not necessarily prevent a code path from being taken that would not have been taken if the transaction were still “viable”. In such cases, it is probably not useful for the user to believe that such a code path was taken, as the transaction will fail and be retried anyway. The debugger can avoid such “false positives” by calling `STM-Validate` after hitting the breakpoint, and ignore the breakpoint if the transaction is no longer viable.

The debugger may also provide a feature that allows the user to abort the debugged transaction, with the option to either retry it from the beginning, or perhaps to skip it altogether and resume execution after the atomic block. Such functionality is straightforward to provide because the compiler already includes code for transferring control for retry or commit, and because most TM implementations provide means for a transaction to explicitly abort itself.

Contention Manager Support

When stepping through an atomic block, it might be useful to change the way in which conflicts are resolved between transactions, for example by making the debugged transaction win any conflict it might have with other transactions. We call such a transaction a *super-transaction*. This feature is crucial for the isolated stepping synchronized debugging mode because the debugged thread takes steps while the rest of the threads are not executing, and therefore there is no point in waiting in case of a conflict with another thread, nor in aborting the debugged transaction. It may also be useful in other debugging modes, because it will avoid the debugged transaction being aborted, causing the "backward-step" phenomenon previously described. This is especially important because the debugged transaction will probably run much slower than other transactions, and therefore is more likely to be aborted.

In some STM and HyTM implementations, particularly those supporting read sharing, orecs indicate only that they are owned in read mode, and do not indicate which transactions own them in that mode (with these implementations, transactions record which locations they have read, and recheck the orecs of all such locations before committing to ensure that none has changed). Supporting the super-transactions with these implementations might seem problematic, since when a transaction would like to get write ownership on an orec currently owned in read mode, it needs to know whether one of the readers owning this orec is a super-transaction. One simple solution is to have the super transaction acquire write ownership of all locations it has read so far, thus allowing any conflicting transaction to identify the owner and check whether it is a super transaction. While this solution will work, it may also cause all other transactions that read these locations to be aborted unnecessarily. A better solution would be to specially mark the orecs a super transaction owns for reading. The STM library (or its contention manager component) would then ensure that a transaction never acquires write ownership of an orec that is currently owned by the super-transaction.

Switching between Debugged Threads

When stopping at a breakpoint, the thread that hit that breakpoint automatically becomes the debugged thread. In some cases though, the user would like to switch to debug another thread after the debugger has stopped at the breakpoint. This is particularly useful when using the isolated steps synchronized debugging mode, because in this case the user has total control over all the threads, and can therefore simulate complicated scenarios of interaction between the threads by taking a few steps with each thread separately.

There are a few issues to consider when switching between debugged threads. The first has to do with hardware transactions when using HyTM: it might be that the new debugged thread is in the middle of executing the HTM-based implementation of an atomic block. Depending on the HTM implementation, attaching the debugger to such a thread may cause the hardware transaction to abort. (In a synchronized debugging mode, it might have already been aborted when the debugger stopped all the threads.) Moreover, because HTM is not assumed to provide any specific support for debugging, we will often want to abort the hardware transaction anyway, and restart the atomic block's execution using the STM-based implementation.

Again, depending on the HTM support available, various alternatives may be available, for example:

1. Switch to the new thread aborting its transaction

2. Switch to the new thread but only after it has completed (successfully or otherwise) the transaction (this might be implemented for example by appropropriate placement of additional breakpoints).

3. Cancel and stay with the old debugged thread.

Another issue to consider is the combination of the super-transaction feature and the ability to switch the debugged thread. Generally it makes sense to have only one super-transaction at a time. If the user switches between threads, it is probably desirable to change the previously debugged transaction back to be a regular transaction, and make the new debugged transaction a super-transaction. As described above, this may require unmarking all orecs owned in read mode by the old debugged transaction, and marking those of the new one.

2.4.2 Viewing and Modifying Variables

Another fundamental feature supported by all debuggers is the ability to view and modify variables when the debugger stops execution of the program. The user provides a variable name or a memory address, and the debugger displays the value stored there and may also allow the user to change this value. As explained earlier, in various TM implementations, particularly those based on STM or HyTM approaches, the current logical value of the address or variable may differ from the value stored in it. In such cases, the debugger cannot determine a variable's value by simply reading the value of the variable from memory. The situation is even worse with value modifications: in this case, simply writing a new value to the specified variable may violate the atomicity of transactions currently accessing it. In this section we explain how the debugger can view and modify data in a TM-based system despite these challenges.

The key idea is to access variables that may be accessed by transactions using the TM implementation, rather than directly, in order to avoid the above-described problems. However, there are several important issues to consider in deciding whether to access a variable using a transaction, and if so, with which transaction.

First, the debugged program may contain *transactional* variables that should be accessed using TM and *nontransactional* variables that can be accessed directly using conventional techniques. A variety of techniques for distinguishing these variables exist, including type-based rules enforced by the compiler, as well as dynamic techniques that determine and possibly change the status of a variable (transactional or nontransactional) at runtime (for example, [21]). Whichever technique is used in a particular system, the debugger must be designed to take the technique into account and access variables using the approrpropriate method. In particular, the debugger should always use transactions to access transactional variables, and nontransactional variables can be accessed as in a standard debugger.[3]

[3]In some TM systems, accessing a nontransactional variable using a transaction will not result in incorrect behavior, in which case we can choose to access all variables with transactions.

For transactional variables, one option is for the debugger to get or set the variable value by executing a "mini-transaction"—that is, a transaction that consists of the single variable access. The mini-transaction might be executed as a hardware transaction or as a software transaction, or it may follow the HyTM approach of attempting to execute it in hardware, but retrying as a software transaction if the hardware transaction fails to commit or detects a conflict with a software transaction.

Note, however, that the goal of the debugger is to show the value of the variable from the point of view of the debugged program, or more precisely, of the debugged thread. Therefore, if the debugger has stopped in the middle of an atomic block execution, and the variable to be accessed has already been accessed by the debugged transaction, then it is often desirable to access the specified variable from the debugged transaction's point of view. This is important because the debugged transaction may have written a value to the variable, that the user may desire to see even though the transaction has not yet committed, and therefore this value is not (yet) the logical value of the variable being examined. Similarly, if the user requests to modify the value of a variable that has been accessed by the debugged transaction, then it may be desirable for this modification to be part of the effect of the transaction when it commits. To support this behavior, the variable can be accessed in the context of the debugged transaction simply by calling the appropriate library function to read the variable as part of the transaction. (We note that it is straightforward to extend existing HyTM and STM implementations to support functionality that determines whether a particular variable has been modified by a particular transaction.)

Note that it is still often better to access variables that were not accessed by the debugged transaction using mini-transactions and not the debugged transaction itself. This is because accessing such variables using the debugged transaction increases the set of locations that the transaction is accessing, thereby making it more likely to abort due to a conflict with another transaction.

In general, it is preferable that actions of the debugger have minimal impact on normal program execution. For example, we would prefer to avoid aborting transactions of the debugged program in order to display values of variables to the user. However, we must preserve the atomicity of program transactions. In some cases, it may be necessary to abort a program transaction in order to service the user's request. For example, if the user requests to modify a value that has been accessed by an existing program transaction, then the mini-transaction used to effect this modification may conflict with that program transaction. In some cases the conflict can occur even if the variable was not accessed by any of the program transactions, due to *false conflicts*, where two transactions conflict even though they do not access any variables in common. In other cases, it may not be possible to determine whether a particular program transaction has already committed, in which case it would not be possible to determine the logical value of a variable that it has modified.

In case the mini-transaction used to implement a user request does conflict with a program transaction, several alternatives are possible. We might choose either to abort the program transaction, or to wait for it to complete (in appropriate debugging modes), or to abandon the attempted modification. These choices may be controlled by preferences configured by the user, or by prompting the user to decide between them when the situation arises. In the latter case, various information may be provided to the user, such as which program transaction is involved, what variable is causing the conflict (or an indication that it is a false conflict), etc.

In some cases, the STM may provide special-purpose methods for supporting mini-transactions for debugging. For example, if all threads are stopped, then the debugger can modify a variable that is not being accessed by any transaction without acquiring ownership of its associated orec. Therefore in this case, if the STM implementation can tell the debugger whether a given variable is being accessed by a transaction, then the debugger can avoid acquiring ownership and aborting another transaction due to a false conflict.

Adding and Removing a Variable from the Transaction's Access Set

As described in the previous section, it is often preferable to access variables that do not conflict with the debugged transaction using independent mini-transactions. In some cases, however, it may be useful to allow the user to access a variable as part of the debugged transaction even if the transaction did not previously access that variable. This way, the transaction would commit only if the variable viewed does not change before the transaction attempts to commit, and any modifications requested by the user would commit only if the debugged transaction commits. This approach provides the user with the ability to "augment" the transaction with additional memory locations.

Moreover, some TM implementations support *early-release* functionality [16]: with early-release, the user can decide to discard any previous accesses done to a variable by the transaction, thereby avoiding subsequent conflicts with other transactions that modify the released variable. If early-release is supported by the TM implementation, the debugger can also support removing a variable from the debugged-transaction's access set.

Displaying the pre-transaction value of the debugged transaction

Although when debugging an atomic block the user would usually prefer to see variables as they would be seen by the debugged transaction, in some cases it might be useful to see the value as it was before the transaction began (note that since the debugged transaction has not committed yet, this *pre-transaction* value is the current logical value of the variable, as seen by other threads). Most STM implementation can provide such functionality because they have to keep track of the pre-transaction value in case that the transaction will be aborted, in which case all locations it tried modifying will have to be restored to their pre-transaction values. Thus, some STM implementations record the value of all variables accessed by a transaction the first time they are accessed. In other STM implementations, the pre-transaction value is kept in the variable itself until the transaction commits, and can thus be read directly from the variable. In such systems, the debugger can display the pre-transaction value of a variable (as well as the regular value seen by the debugged transaction).

Getting values from conflicting transactions

In some cases, it is possible to determine the logical value of a variable even if it is currently being modified by another transaction. As described above, it may be possible for the debugger to get the pre-transaction value of a variable accessed by a transaction. If the debugger can determine that the conflicting transaction's linearization point has not passed, then it can display the pre-transaction value to the user. How such a determination can be made depends on the particular STM implementation, but in many cases this is not difficult.

Another potentially useful piece of information we can get from the transaction that owns the variable the user is trying to view is the *tentative value* of that variable—that is, the value as seen by the transaction that owns the variable. Specifically, the debugger can inform the user that the variable is currently accessed by a software transaction, and give the user both the current logical value of the variable (that is, its pre-transaction value), and its tentative value (which would become the logical value if the transaction were to commit successfully at that point).

2.4.3 Atomic Snapshots

The debugger can allow the user to define an *atomic group* of variables to be read and/or modified atomically. Such a feature provides a powerful debugging capability that is not available for conventional programs: the ability to get a consistent view of multiple variables even in unsynchronized debug mode, when threads are running and potentially modifying these variables. (It can also be used with synchronized debugging when combined with the delayed breakpoint feature; see Section 2.4.5.)

Implementing atomic groups using TM is simply done by accessing all variables in the group using one transaction. The variables in the group are read using a single transaction. As for modifications, when the user modifies a variable in an atomic group, the modification does not take effect until the user asks to commit all modifications to the group, at which point the debugger begins a transaction that executes these modifications atomically. The transactions can be managed by HTM, STM or HyTM.

Note, however, that it is not guaranteed that the group's variables still have the displayed values at the point the user is asking to commit the modifications to the group. This may result in unexpected behavior if, for example, the user's intention is to assign the value of one variable in the group to another. We can thus extend this feature with a *compare-and-swap* option, which modifies the values of the group's variables only if they contain the previously displayed values. This can be done by beginning a transaction that first rereads all the group's variables and compares them to the previously presented values (saved by the debugger), and only if these values all match, applies the modifications using the same transaction. If some of the values did change, the new values can be displayed.

Finally, the debugger may use a similar approach when displaying a compound structure in an unsynchronized debug mode, to guarantee that it displays a consistent view of that structure. Suppose, for example, that the user views a linked list, starting at the head node and expanding it node-by-node. Because in unsynchronized debugging mode the list might change while being viewed, reading it node-by-node might display an inconsistent view of the list. The debugger can use a transaction to re-read the nodes leading to the node the user has just expanded, thereby avoiding such inconsistency.

2.4.4 Watchpoints

Many debuggers support *watchpoint* functionality, allowing a user to instruct the debugger to stop when a particular memory location or variable is modified. More sophisticated watchpoints, called *conditional watchpoints*, can also specify that the debugger should stop only when a certain predicate holds (for example, that the variable's value is bigger than some number).

Watchpoints are sometimes implemented using specific hardware support, called hw-breakpoints. If no hw-breakpoint support is available, some debuggers implement watchpoints in software, by executing the program step-by-step and checking the value of the watched variable(s) after each step, which results in executing the program hundreds of times slower than normal.

We describe here how to exploit TM infrastructure to stop on any modification or even a read access to a transactional variable. The idea is simple: because the TM implementation needs to keep track of which transactions access which memory locations, we can use this tracking mechanism to detect accesses to specific locations. Particularly, with the HyTM implementation described in Section 2.2, we can mark the orec that corresponds to the memory location we would like to watch, and invoke the debugger whenever a transaction gets ownership of such an orec. In the hardware code path, when checking an orec for a possible conflict with a software transaction, we can also check for a watchpoint indication on that orec. Depending on the particular hardware TM support available, it may or may not be possible to transfer control to the debugger while keeping the transaction viable. If not, it may be necessary to abort the hardware transaction and retry the transaction in software.

The debugger can mark an orec with either a *stop-on-read* or *stop-on-write* marking. With the first marking, the debugger is invoked whenever a transaction gets read ownership of that orec (note that some TM implementations allow multiple transactions to concurrently own an orec in read mode), and with the latter, it is invoked only when a transaction gets write ownership of that orec. When invoked, the debugger should first check whether the accessed variable is one of the watchpoint's variables (multiple memory locations may be mapped to the same orec). If so, then the debugger should stop, or, in the case of a conditional watchpoint, evaluate a predicate to decide whether to stop. Note that the predicate may be dependent on additional variables; we discuss how the debugger handles these cases later.

Stopping the program upon access to a watchpoint variable can be done in one of two ways:

1. *Immediate-Stop:* The debugger can be invoked immediately when the variable is accessed. While this gives the user control at the first time the variable is accessed, it has the disadvantage that the first value written by the transaction to the variable may not be the actual value finally

written by the transaction: the transaction may later change the value written to this variable, or abort without modifying the variable at all. Since the transaction seems to be executed in isolation, these intermediate values are not visible to anyone except for the thread executing the transaction. Thus, in many cases, the user would not care about these intermediate values of the variable, or about accesses done by transactions that do not eventually commit, especially with conditional watchpoints when the user asks to only stop when the written values satisfies some predicate.

2. *Stop-on-Commit:* This option overcomes the problems of the immediate-stop approach, by delaying the stopping to the point when the transaction commits. That is, instead of invoking the debugger whenever a marked orec is acquired by a transaction, we invoke it when a transaction that owns the orec commits; this can be achieved for example by recording an indication that the transaction has acquired a marked orec when it does so, or simply by checking for marked owned orecs when committing successfully. With this method, the user sees the value actually written to the variable, since at that point no other transaction can abort the triggering transaction anymore. While this approach has many advantages over the immediate-stop approach, it also has the disadvantage that the debugger will never stop on an aborted transaction that tried to modify the variable, which in some cases might be desirable. Therefore, we believe that it is desirable to support both options, allowing the user to choose between them. Also, when using the stop-on-commit approach, the user cannot see how exactly the written value was calculated by the transaction, although this problem can be mitigated by the replay debugging technique described in Section 2.4.6.

While the above description assumes a TM implementation that uses orecs, the tecniques we propose are also applicable to other TM approaches. For example, in object-based TM implementations like the one by Herlihy et. al. [16], we can stop on any access to an object since any such access requires opening the object first, so we can change the method used for opening an object to check whether a watchpoint was set on that object. This might be optimized by recording an indication in an object header or handle that a watchpoint has been set on that object.

Dynamic Watchpoints

In some cases, the user may want to put a watchpoint on a field whose location may dynamically change. Suppose, for example, that the user is debugging a linked list implementation, and wishes to stop whenever some transaction accesses the value in the first node of the list, or when some predicate involving this value is satisfied. The challenge is that the address of the field storing the value in the first node of the list is indicated by `head->value`, and this address changes when `head` is changed, for example when inserting or removing the first node in the list. In this case, the address of the variable being watched changes. We denote this type of a watchpoint as a *dynamic watchpoint*. (We note that this debugging technique is not specific for transactional programs; it will be as useful for regular programs.)

We can implement a dynamic watchpoint on `head->value` as follows: when the user asks to put a watchpoint on `head->value`, the debugger puts a regular watchpoint on the current address of `head->value`, and a special debugger-watchpoint on the address of `head`. The debugger-watchpoint on `head` is special in the sense that it does not give the control to the user when `head` is accessed: instead, the debugger cancels the previous watchpoint on `head->value` at that point, and puts a new watchpoint on the new location of `head->value`. That is, the debugger uses the debugger-watchpoint on `head` to detect when the address of the field the user asked to watch is changed, and changes the watchpoint on that field accordingly.

Multi-Variable Conditional Watchpoints

There are two kind of conditional watchpoints that may be conditioned on multiple variables. In the first kind, the watchpoint is put on only one variable, but the condition may include other variables as well. For example, stop when variable `x` changes only if the new value of `x` equals another variable y. In the other kind of a watchpoint, the user asks to stop whenever some predicate that is dependent on multiple variables is satisfied. For example, the user asks to stop only if the sum of two variables is greater than some value. Here, the user asks the debugger to stop on the first memory modification that satisfies the predicate. We denote such watchpoints as *multi-variable conditional-watchpoints*, and the variables that should be watched as the *watched variables.* Note that in the second type of a watchpoint *all* variables of the predicate should be watched.

To implement a multi-variable conditional watchpoint, the debugger can place a watchpoint on each of the watched variables, and evaluate the predicate whenever one of these variables is modified. We denote by the *triggering transaction* the transaction that caused the predicate evaluation to be invoked. One issue to be considered is that evaluating the predicate requires accessing the other variables (which may or may not be watched). This can be done as follows:

- The debugger uses the stop-on-commit approach, so that when a transaction that modifies any watched variables commits, we stop execution either before or after the transaction commits. In either case, we ensure that the transaction still has ownership of all of the orecs it accessed, and we ensure that these ownerships are not revoked by any other threads that continue to run, for example by making the triggering transaction a super-transaction.

- When evaluating the predicate, the debugger distinguishes between two kinds of variables: ones that were accessed by the triggering transaction, which we denote as *triggering variables*, and the rest which we denote as *external variables.* External variables might be accessed by using the stopped transaction, or by using another transaction initiated by the debugger. In the latter case, because the triggering transaction is stopped and retains ownership of the orecs it accessed while the new transaction that evaluates the external variables executes, the specified condition can be evaluated atomically.

- While reading the external variables, conflicts with other transactions that access these variables may occur. One option is to simply abort the other transaction. However, this may be undesirable, because we may prefer that the debugger has minimal impact on program execution. As discussed in Section 2.4.2, it is possible in some cases to determine the pre-transaction value for the watched variable without aborting the transaction that is accessing it.

2.4.5 Delayed Breakpoints

Stopping at a breakpoint and running the program step-by-step affects the behavior of the program, and particularly the timing of interactions between the threads. Placing a breakpoint inside an atomic block may result in even more severe side-effects, because the behavior of atomic blocks may be very sensitive to timing modifications since they may be aborted by concurrent conflicting transactions. These effects may make it difficult to reproduce a bug scenario.

To exploit the benefits of breakpoint debugging while attempting to minimize such effects, we suggest the *delayed breakpoint* mechanism. A delayed breakpoint is a breakpoint in an atomic block that does not stop the execution of the program until the transaction implementing the atomic block *commits*. Besides the advantage of a smaller impact on execution timing, this technique also avoids stopping execution in the case that a transaction executes the breakpoint instruction, but then aborts. In many cases, it will be preferable to only stop at a breakpoint in a transaction that subsequently commits.

Delayed breakpoints encourage debugging methodology where the user reasons about the whole effect of an atomic block, and places assertions inside the atomic block to verify that it doesn't violate an invariant of the system. Note that the assertions are evaluated atomically as part of the atomic block's execution. The user can place delayed breakpoints on these assertions, stopping when an atomic block execution commits and violates the system invariant.

To support delayed breakpoints, rather than stopping the program execution when an instruction marked as a delayed breakpoint is executed, we merely set a flag that indicates that the transaction has hit a delayed breakpoint, and resume execution. Later, upon committing, we stop the program execution if this indication is set.

One simple type of a delayed breakpoint stops on the instruction *following* the atomic block if the transaction implementing the atomic block hit the breakpoint instruction in the atomic block. This kind of delayed breakpoint can be implemented even when the transaction executing an atomic block is run using HTM. The debugger simply replaces the breakpoint-instruction in the HTM-based implementation to branch to a piece of code that executes that instruction, and raises a flag indicating that the execution should stop on the instruction following the atomic block. This simple approach has the disadvantage that the values written by the atomic block may have already been changed by other threads when execution stops, so the user may see a state of the world that differs from the state when the breakpoint instruction was hit. Moreover, if the transaction is executed in hardware, then unless there is specific hardware support for this purpose, the user would not be able to get any information about the transaction execution (like which values were read/written, etc.).

On the other hand, if the atomic block is executed by a software transaction (or if special hardware support is available), we can have a more powerful type of a delayed breakpoint, which stops *at the commit point* of the executing transaction. More precisely, the debugger tries to stop at a point during the commit operation of that transaction at which the transaction is guaranteed to commit successfully, but no other transaction has seen its effects on memory. This can be done by having the commit operation check the flag that indicates if a delayed-breakpoint placed in the atomic block was hit by the transaction, and if so do the following:

1. Make the transaction a super-transaction. (This step is only necessary in unsynchronized debugging mode, when the transaction can still be aborted by other threads.)

2. Validate the transaction. That is, make sure that the transaction can commit. If validation fails, abort the transaction, fail the commit operation, and resume execution.

3. Give control to the user.

4. When the user asks to continue execution, commit the transaction. Note that, depending on how super-transactions are supported, a lightweight commit may be applicable here if we can

be sure that the transaction cannot be aborted after becoming a super-transaction.

The idea behind the above procedure is simple: guarantee that all future conflicts will be resolved in favor of the transaction that hit the breakpoint, check that the transaction can still commit, and then give control to the user, who can subsequently decide to commit the transaction.

At Step 3 the debugger stops the execution of the commit operation and gives control to the user. This is the point at which the user gets to know that a committed execution of the atomic block has hit the delayed breakpoint. At that point, the user can view various variables, including those accessed by the transaction, to try to understand the effect of that execution. In Section 2.4.6, we describe other techniques that can give the user more information about the committed transaction's execution at that point.

Combining with Atomic Groups

One disadvantage of using a delayed breakpoint is that if the user views variables *not* accessed by the transaction, the values seen are at the time the debugger stops rather than the time of the breakpoint-instruction execution. Therefore, it may be useful to combine the delayed breakpoint mechanism with the atomic group feature (Section 2.4.3): with this combination, the user can associate with the delayed breakpoint an atomic group of variables whose values should be recorded when the delayed breakpoint instruction is executed. When the delayed breakpoint instruction is hit, besides triggering a breakpoint at the end of the transaction, the debugger gets the atomic group's value (as described in Section 2.4.3), and presents it to the user when it later stops in the transaction's commit phase.

2.4.6 Replay Debugging for Atomic Blocks

It is useful to be able to determine how the program reached a breakpoint. *Replay debugging* has been suggested in a variety of contexts to support such functionality, and support ranging from special hardware to user libraries have been proposed (see [26, 31] for two recent examples).

Replay debugging for multithreaded concurrent applications generally requires logging that can add significant overhead. In this section, we explain how STM infrastructure can be exploited to support replaying atomic blocks, without the need for additional logging. We also explain how the user can even modify data, observe how execution would have proceeded had it read different values, and even choose to commit that execution instead of the original one. To our knowledge, previous replay debugging proposals do not support such functionality.

The idea behind our replay debugging technique is to exploit the fact that the behavior of most atomic blocks is uniquely determined by the values it reads from memory[4]. Some STM implementations record values read by the transaction in a readset. Others preserve these values in memory until the transaction commits, at which point the values may be overwritten by new values written by the transaction. In either case, as long as the transaction is valid and can still commit successfully, it should be possible to provide the debugger access to the values of the variables as seen by the transaction. We denote these values as the *pre-transactional* values of the variables. Doing so will allow the debugger to reconstruct execution of the transaction, as explained in more detail below:

- The debugger maintains its own write-set for the transaction. This is necessary to allow the debugger to determine the values returned by reads from locations that the transaction has previously written. The replay begins with an empty write set.
- The replay procedure starts from the beginning of the debugged atomic block, and executes all instructions that are not STM-library function calls as usual.
- The replay procedure ignores all STM library function calls except the ones that implement the transactional read/write operations.
- When the replay procedure reaches a transactional write operation, it writes the value in the write set maintained by the debugger.

[4]We call such atomic blocks *transactionally deterministic*. While the techniques described in this section may be useful even for blocks that the compiler cannot prove are transactionally deterministic, in this case the user should be informed that the displayed execution might not be identical to the one that triggered the breakpoint.

- When the replay procedure reaches a transactional read operation, it first searches the value for the read variable in the write set maintained by the debugger. If the value is there, this is the returned value of that transactional read operation. Otherwise, the pre-transactional value of the variable is returned.

As long as the debugged transaction retains ownership of orecs it acquired during the original execution,[5] the transaction stays valid, and all variables it has read retain their pre-transactional values. Therefore the replayed execution is faithful to the original.

Replay debugging functionality can be combined with various other features we have described. For example, by combining replay debugging with the delayed breakpoint feature described in Section 2.4.5, we can create the illusion that control has stopped inside an atomic block, although it has actually already run to its commit point. Then, the replay functionality allows the user to step through the remainder of the atomic block before committing it. It is even possible to allow experimentation with alternative executions of a debugged atomic block, for example by changing values it reads or writes. In some cases, we may wish to do so without affecting the actual program execution. In other cases, we may prefer to change the actual execution, and subsequently resume normal debugging. One way to handle the latter case is to abort the current transaction *without releasing orecs*, and replay it up to the point at which the user wishes to change something. This way, we guarantee that the transaction will reexecute up to this point identically to how it did in the first place.

Combining replay debugging with other debugger features we have proposed can support a rather powerful debugging environment for transactional programs.

[5] In our description we assumed that no other thread is running while the transaction is being replayed, so the transaction trivially retains ownership of all orecs it acquired. If halting all other threads during the replay is not possible, the debugger can make the transaction a super transaction, and verify that no ownerships were revoked during the replay.

2.5 Summary

This chapter explored how to provide debugging support for transactional programs. It discussed how to adjust basic debugging features to work with transactional programs, as well as how to provide new, more advanced features that we believe to be useful with the different nature of transactional programs. In the next chapter we describe the tm_db library, which we developed to support some of these debugging features for various STM algorithms.

Chapter 3

Practical Transactional Debugging Support: The TMDB library

In this chapter we present more technical details on how to support debugging of transactional programs in real, commercial debuggers. The chapter introduces tm_db, a library that provides debuggers with a general debugging support for transactional programs. The library supports various STM algorithms, and helps debuggers provide users with transactional debugging features that are independent of the particular TM runtime internals. Furthermore, while the library currently supports only the STM algorithms provided by the SkySTM library, it is designed so that it can be extended to work with additional TM runtimes, without needing to change the debuggers using it.

The chapter presents the various debugging features the library supports, its design, and how a debugger can use it to provide debugging support for transactional programs.

3.1 Introduction

In this chapter we focus on how some of the debugging features described in Chapter 2 can be implemented in a real, commercial debugger. In particular, we describe `tm_db`, a library that we built to aid debuggers with providing debugging support for transactional programs.

One of the first observations that we had when switching from describing transactional debugging techniques to actually implementing them is that many debuggers do not really run as part of the debugged program process space; they only provide the illusion that they do. Therefore, the implementation techniques described in Chapter 2, in which debugging features use the STM runtime to run transactions could not be used in practice. Instead, as described in Section 3.3, we had to *simulate* the execution of such transactions with code that runs in a remote process, while the debugged process is stopped.

Another challenge in designing the `tm_db` library was in defining its interface with the debugger so that it can support debugging with different transactional memory algorithms and runtimes. Today, the research literature encompasses many different STM algorithms: some update objects in place, some log undo operations in case a transaction is aborted; some detect conflicts when objects are accessed, some only when a transaction attempts to commit; some support implicit privatization, some do not. Despite these differences, we believe that the basic debugging needs for transactional programs are similar with all these algorithms, and we strove to define an interface to the debugger that is independent of the particular TM runtime in use.

To this point, the `tm_db` library works with the SkySTM runtime [20], which supports a wide range of transactional memory algorithms and contention management strategies. As we explain in Section 3.3, we designed the `tm_db` library so that it can be easily extended to support additional TM runtime libraries and algorithms, without needing to change the debuggers that are using it. Recently, the Sun Studio product group in Sun Microsystems used the `tm_db` library for preliminary debugging support for transactional programs in the Sun Studio `dbx` debugger, which was extended with additional debugging functionality for this purpose.

The rest of the chapter is organized as follows. In Section 3.2 we describe the debugging features supported by tm_db, explain how they address debugging with different STM algorithms, and provide examples of how the debugger can use these features when providing debugging support. In Section 3.3 we describe the design of the library and how it can be integrated in a real debugging environment. In Section 3.4 we describe our experience implementing the solution for the SkySTM runtime, and we conclude in Section 3.5.

3.2 Debugging Transactional Programs

This section describes basic debugging features we believe are esssential for transactional debugging, and how they are provided by tm_db.

3.2.1 Logical Values

STM runtimes often deploy complex schemes to preserve the valuable illusion of simplicity provided by the transactional model — schemes may be exposed and confuse the user if a transactional program is debugged using a standard debugger. For example, consider a simple phase-based program, where the phase is governed by a shared counter. Suppose the user halts the program at a breakpoint, examines the counter, and sees that the program is at Phase 3. Can the user assume that the effects of all Phase 2 transactions are reflected in memory? In STM runtimes that use deferred updates, some Phase 2 transactions may have committed, but their effects may not have been written to memory. Examining memory may confuse the user, as it may be seen as if the program is at Phase 3 before some Phase 2 operations are completed. Similarly, the atomicity property may be violated with STM runtimes that use undo logs (e.g., [30]), where some Phase 2 transactions may have aborted, but their effects may not yet have been undone.

Therefore, as described in Chapter 2, to maintain the atomicity illusion, a debugger must not naïvely fetch a variable value from memory, but rather interoperate with the STM runtime and return the value as it would be seen by an independent mini-transaction reading the variable. The tm_db library supports this functionality by providing the *logical values* of memory locations, which expose the effects of a transaction atomically (all at once), and exactly at the transaction's commit point.[1]

In more detail, we define the logical value of a memory location L to be the latest value written to L by either a committed transaction (whether or not that value actually appears in L), or a non-transactional write.[2] When examining logical values, a transaction's effect is exposed atomically when it commits. By providing logical values, the tm_db library abstracts away details of the STM runtime, like whether it uses the deferred writes or the in-place writes approach.

Note that the logical value does not reflect tentative writes that were done by transactions that have not yet committed; thus, it may not be the best candidate for presenting values of variables that were modified by the debugged transaction, when seeing these tentative values may be important (see Section 2.4.2 for details). We later describe how tm_db helps the debugger to provide information about such tentative writes when presenting data to the user.

3.2.2 Transaction Identity

To communicate information about transactions between the user and the debugger (and between the debugger and tm_db), transactions need to be uniquely identified (similar to the way threads are uniquely identified by thread ids).

We distinguish between three notions of interest when identifying a transaction. An *atomic block* is a *lexical* scope, corresponding to the lines of code executed by a transaction. A *logical transaction* occurs at run time when a thread executes an atomic block. The same atomic block can produce multiple logical transactions, one for each of its successful executions.[3] Finally, a logical transaction

[1] By "commit point" we refer to the point at which the transaction logically takes effect.

[2] When the underlying TM does not provide strong atomicity, this definition assumes that there are no concurrent transactional and non-transactional writes to the same location.

[3] A successful execution does not necessarily mean that the transaction has successfully committed – it might have

```
  Thread   Latest  TxId   Status       Atomic Block

  t@1      <None>                      <None>
  t@2      2.1907.0       Committed    PushHead+0x0008
  t@3      3.2217.1       Active       PushTail+0x0008
> t@4      4.2082.0       Aborting     PushHead+0x0008
  t@5      5.2107.0       Committing   PushHead+0x0008
  t@6      6.2210.0        Invalid     PushTail+0x0008
```

Figure 3.1: Transactions Ids, Statuses, and Atomic blocks.

can produce a sequence of *physical transactions*, because an execution of a logical transaction may be rolled back and retried, possibly several times.

To capture the distinction between logical and physical transactions, the library represents a transaction as a triple T.L.P, where T is the thread executing the transaction, L is the total number of logical transactions completed by thread T, and P is the number of physical transactions that failed executing the current logical transaction. For example, Transaction 3.4.1 indicates the 2nd try of the 5th logical transaction of thread 3. Thus, when stopping at two different points, the user can tell what progress each thread has made: for example whether it is still executing the same physical transaction, the same logical transaction, and so on. An atomic block is identified by the address of its first instruction, which is easily translated to a specific function name and offset, or to a file and line number (when the program is compiled with debugging information).

The library provides the transaction and atomic block id for the *latest transaction* begun by each thread (even if the transaction has already completed). Figure 3.1 shows a usage example,[4] in which a debugger uses the library to present the transaction and atomic block ids of the latest transactions for all running threads, as well as their statuses, which we describe next.

3.2.3 Transaction Status

The library represents a transaction's *status* using three fields:

been self-aborted.

[4] All usage examples are from a prototype integrated with dbx.

- The IsRunning flag indicates whether the transaction is still running, or has completed.

  We say that a transaction is not completed as long as there are still some operations to be done on its behalf by the STM runtime (this includes any cleanup operations that have to be done after a transaction is aborted or committed). Thus, a transaction may be still running even after it has logically committed (taken effect), or after it is determined that it must be aborted. While we are aware that the value of the IsRunning flag is not well defined for any possible STM algorithm, we believe that it is well defined for all STM algorithms we are aware of and decided to include this information in the transaction's status.

- The transaction's State can be one of the following values: Active, Committed, Aborted, and Invalid .

  – An Active transaction is still capable of committing successfully (meaningful only for running transactions).

  – An Invalid Transaction can no longer commit successfully (for example, it may have read something modified by another transaction), but is not yet aware of it, and not yet in the process of aborting. Such transactions may still be executing user code, and are sometimes referred to as "zombie" or "doomed" transactions.

  – A Committed transaction has already committed successfully. If IsRunning is true, the transaction may not have completed post-commit cleanup operations, such as executing deferred writes. Still, the logical values of all locations it has written already reflect the new written values.

  – An Aborted transaction has failed to commit successfully. If IsRunning is true, the transaction may not have completed some post-abort cleanup operations, such as undoing in-place writes.[5]

[5] The library is unaware whether the underlying TM uses deferred or in-place writes. It simply reports the state and whether the transaction is running; the user can decide whether a particular state is interesting based on specific knowledge of the TM runtime.

- The IsWaiting flag reports whether the transaction is blocked by the underlying TM, waiting for another transaction. If so, the address for which it is waiting can sometimes be provided.[6] Different TM implementations may have blocked transactions in any one of the above states. For example, a transaction may be Active while waiting for a location X, and then become Invalid because another location that it has accessed is modified. The IsWaiting flag for the transaction may continue to be `true` for a while, until the transaction finds out that it can no longer commit successfully, and abort. The IsRunning value for a blocked transaction must be true, though.

Note that even though the library conveys transaction status via these three fields, a debugger may display it differently. For example, in Figure 3.1, the debugger does not display the IsRunning value; instead, it uses Commited and Committing to distinguish a completed transaction that committed (thread t@2) from a running transaction that is logically committed but has not yet completed (thread t@5). As an another example, some debuggers may not allow users to stop and examine aborted or invalid transactions, in which case the user may only need to see whether the thread is currently executing a transaction, and which transaction. (The debugger may still need to examine the State field to determine whether a transaction is aborted or invalid, and avoid stopping in this case.)

3.2.4 Read, Writes, Conflicts, and Coverage

A transaction T *covers* a location L if a write access to L by another transaction[7] would cause a conflict with T. A transaction covers all locations it has read or written. A *false conflict* occurs when the conflict is on a location that the transaction covers but has not explicitly accessed. This typically happens when the underlying TM maps the locations to the same "protection unit" (such

[6] Whether or not tm_db can provide this additional information depends on the particular STM runtime in use. The library interface allows a particular TM runtime not to support this feature, as we later describe in Section 3.3.3.

[7] We only consider write accesses by transactions because tm_db does not assume that strong atomicity is supported, and thus that conflicts between transactional and non-transactional memory accesses can be detected.

```
> tx coverage &g_list.Head->next->key

  Tid    TxID & Status    Coverage Type   Written   Read

  t@2    2595.0  Active    Read & Write    Yes       Yes
  t@6       1.0  Active    Read & Write    Yes       No
  t@4    2023.0  Active    Read & Write    No        No
```

Figure 3.2: Coverage for a given variable

as the ownership records described in Chapter 2) as that of accessed locations.

Coverage can be refined to *read* or *read & write* coverage, where we say that a transaction T has a *read & write* coverage of a location if even a read access to the location by another transaction would cause a conflict with T. In addition, because some TM runtimes allow multiple transactions that wrote to the same location to commit as long as neither read it, we also provide a *write-only* coverage type.

For a location L and transaction T, the library supports checking whether T accessed L, whether T covers L, and if, so, for reading, writing, or both. Distinguishing coverage from access is helpful for distinguishing true and false data conflicts. Access and coverage information is recorded when the access occurs in the user's code, and not when the transaction physically writes the location, or acquires ownership of it. The latter events might occur long after the actual access if the underlying TM uses deferred updates (when written locations are modified only after the transaction has logically committed) or lazy acquisition (when write ownership is granted only when the transaction tries to commit). Reporting accesses as they happen in the user's code is easier for the user to understand, and is independent of the underlying TM.

Figure 3.2 shows how the debugger can use this information to provide full access and coverage information for the key field in a linked list node. In this example, thread t@2 has read and written the key field, while thread t@6 has only written it, but still covers it for both reading and writing, meaning that it read another location that maps to the same "protection unit" by the underlying TM (a false conflict). On the other hand, thread t@4 did not access key at all, but covers it anyway for

```
> printConf

Tid   TxID & Status    Coverage Type   Written    Read

t@2   2595.0  Active   Write           Yes
t@6      1.0  Active   Write           Yes
t@4   2023.0  Active   Write           Yes
===========
0x10019dc48

Tid   TxID & Status    Coverage Type   Written    Read

t@2   2595.0  Active   Read & Write    Yes        Yes
t@6      1.0  Active   Read & Write    Yes        No
t@4   2023.0  Active   Read & Write    Yes        No
===========
0x10018bde0
```

Figure 3.3: Full conflicts report (the `Read` column is empty for locations that are not covered for reading).

both reading and writing (another false conflict). Note that all transactions still have Active status, which is possible with an STM that uses lazy conflict detection, as long as none of the owners has committed.

The debugger can also use this functionality to display access and coverage information by the current debugged transaction and for each variable in its variables/watch window. Also, if the transaction's status indicates it is blocked, the function can find the blocking transaction (recall that tm_db may provide the address for which a transaction is waiting when it is blocked.) This is especially important when debugging in a *isolated stepping* mode (Chapter 2), as the thread executing the blocking transaction may not be taking any steps; detecting the blocking transaction (and thread) enables stepping it to completion, allowing the debugged transaction to keep executing.

In addition to access and coverage information for a given address, the library provides the ability to iterate though the set of all locations a transaction has accessed, either for reading or for writing. The iterator provides the address and value written (or read) for each location. This high-level interface hides whether the underlying TM implementation maintains explicit write sets, or instead uses an undo log.

One interesting use of the write set iterator is for providing information on *all* locations currently involved in conflicts, as illustrated in Figure 3.3. Since each address involved in a conflict must be written by some transaction, the debugger can build a list of potentially conflicted addresses by iterating through the write sets of all running transactions, and then checking (using the coverage query functionality) which of these addresses is covered by more than one running transaction. Also, as we later describe, the debugger may use the write set iterator when displaying variables that were written by the debugged transaction.

Finally, the access and coverage information is provided for the latest transaction of each thread regardless of its status, even if the transaction has already completed. The debugger can choose, for each of its commands, whether to take into account already completed transactions. (For example, the user may be interested in seeing the set of writes done by the previous, completed transaction, but may not be interested in seeing conflicts with these writes.)

Sub-word Accesses

An interesting question is the granularity the runtime TM provides with respect to non-transactional accesses. Almost all STM runtimes disallow concurrent transactional and non-transactional access to the same location, but the notion of a "location" varies from one STM to another. In many STMs, a location is a single or double word. Thus, *if a local variable that is accessed non-transactionally happens to lie in the same physical word with a transactional variable, the system may function incorrectly.* Some other STM runtimes, like SkySTM [20], provide sub-word granularity: if a transaction writes a certain byte in a word, neighboring bytes can be safely written non-transactionally at the same time. To handle such differences in granularity, the write set iterator also provides a mask showing which bytes are affected. (For word-granularity TM runtimes, this mask will always be all ones.)

The mask information allows a debugger to precisely determine whether a particular variable was accessed by a transaction. This way, in the above example where a variable v that is accessed non-transactionally is in the same physical word with a variable that is accessed by some transaction, the debugger will show that v is accessed transactionally (thus indicating a bug) if the underlying TM does not provide sub-word granularity with respect to non-transactional writes.

3.2.5 Usage Example: Viewing Data

As noted, logical values do not always represent the data from the point of view of the debugged program, as they hide any tentative values that might have been written by the debugged transaction to the examined variables. In terms of the functionality provided by tm_db, the debugger can easily present the data from the point of view of the debugged transaction by providing the user with the logical value if the debugged transaction has not written the examined location, or with the value returned by the write set iterator otherwise. We denote this as the *transactional view* of the data.

Note that when the underlying TM provides sub-word granularity with respect to non-transactional writes, it is possible that only some of the bytes of an examined location were written by the debugged transaction, in which case the debugger may need to combine some bytes of the value returned by the write set iterator with bytes of the logical value. The following is an interesting example where it may occur. Suppose that we have an array of Booleans:

```
bool flag[#threads]
```

Let Tx1 be a transaction that writes flag [1] transactionally, Tx2 a transaction that writes flag [2] transactionally and T3 be a thread that writes flag [3] non-transactionally. Suppose the user asks to see the value of the double word containing flags 0-7, at a time when Tx1 is the debugged transaction and has not yet committed, Tx2 is committed but has not yet completed a deferred update to flag [2], and T3 has already executed the non-transactional write to flag [2]. The presented value is assembled from the write sets of Tx1 and Tx2, as well as the memory updated in place by T3; it is the library's responsibility to build the logical value from the combination of flag [2]'s value in

Tx2's write set and the in-memory value of flag [3], and the debugger's responsibility to combine the result with the tentative value of flag [1] returned by the write set iterator of Tx1.

Local variables present a slightly different challenge. Some TMs provide methods for a transaction to write local variables without paying the overhead of synchronizion, but nevertheless guaranteeing that changes will be undone if the transaction aborts. Isolation for these local writes is usually not enforced because it is assumed that the written variables are not accessed by other threads. At this point, the library provides no special support for local writes beyond the isolation guarantees provided by the underlying TM. A user who examines a local variable accessed by another transaction may observe the other transaction's ongoing modifications to the variable. In practice, we do not expect it to be a problem because the local, non-isolated write functionality is usually only used for stack variables, which are only examined for the debugged transaction.

Finally, while it usually makes sense to present the transactional view of examined variables, it is sometimes useful to override this functionality and examine the actual physical values in memory. Privatization [35] is one such example, when a thread uses a transaction to isolate a region of memory, rendering it inaccessible to other threads, and then accesses it non-transactionally. If, when accessed non-transactionally, the logical values in the memory region differ from those in memory, perhaps because some transaction is still in the process of writing committed values to the region, then this non-transactional access is unsafe.[8] Comparing the transactional and the physical views of the memory region will reveal such an unsafe access. Indeed, the debugging functionality added for transactional programs in `dbx` presents the transactional view of the data by default, but also allows turning off this functionality and displaying the in-memory value like with a regular program.

[8] Such an unsafe access may happen either because the underlying TM does not provide appropriate implicit privatization support, or because the program's logic to isolate the memory region is flawed.

Event name	Trigger	Reporting	Monitoring	Report time
TxBegin	Tx begins	Reporting thread Tx Type: first, retry	Reporting thread	immediate
TxCommit	Tx committed	Reporting thread	Reporting thread	immediate
TxAbort	Tx aborted	Reporting thread, Abort reason: - reads-invalid, - writes-invalid, - timeout, - self-abort	Reporting thread, Abort reason	immediate
TxAbortOther	Tx aborts another	Reporting thread, Aborted thread, Conflict type: - read-write, - write-read, - write-write	Reporting thread, Aborted thread, Conflict type	immediate or deferred

Figure 3.4: Transactional Events. For each event type the table describes the triggering condition (in the Trigger column), the reporting parameters (in the Reporting column), the monitoring parameters (in the Monitoring column), and whether the reporting is immediate or deferred to commit time (in the Report time column).

3.2.6 Transactional Events

One of the important features of a debugger is to allow the user to track and stop when various events occur. A breakpoint allows stopping when the "executing a given instruction" event is about to occur; a watchpoint corresponds to the "accessing a given location" event, and so on.

Transactional programs introduce new event types that the user may want to track or to trigger breakpoints on. Figure 3.4 shows the four basic event types that can be monitored by tm_db. When an event is triggered, information is reported to the user in the form of *reporting parameters*. For example, all events report which thread triggered the event. TxAbort reports why the transaction aborted: whether a conflict was triggered with earlier reads or with earlier writes; whether the abort is due to a timeout waiting to access an address (which address?), or did the transaction explicitly abort itself. TxAbortOther reports which other thread was aborted, and why (type of conflict).

One of the goals of tm_db is to introduce minimal intervention until an event of interest occurs. This is especially important when debugging multithreaded programs, where any intervention may cause a bug to disappear. One way to achieve this goal is to *filter* events in the TM runtime using *monitoring parameters*. With such filtering functionality the debugged thread is not stopped until the event happens with the specified value of the monitoring parameters. For example, stop only when a transaction *of a given thread* is aborted, or aborted *for a specific reason*. This runtime filtering mechanism helps users narrow down the specification of the event they would like to track, and avoid interrupting the program until it occurs. Figure 3.4 shows the supported monitoring parameters for each event type.

Finally, sometimes it makes sense not to halt a triggering transaction immediately, but rather to wait until the transaction is committed or aborted. For example, we noticed that when one transaction aborts another, stopping immediately often causes the aborting transaction itself to be aborted, presumably because there is a long delay between when the triggering thread is stopped and the time that the other threads are stopped. Also, like with delayed breakpoints (Section 2.4.5), deferring the breakpoint may reveal a more complete picture of the transaction that triggered the event. On the other hand, some data not accessed by the transaction may be out of date. For these reasons, TxAbortOther reporting can be either immediate or deferred.

3.2.7 Scopes

A monitoring *scope* is another runtime filtering tool provided to reduce the number of times a debugged program needs to be halted. With scopes, a particular event can be monitored for a specific duration. In particular, a thread T can monitor an event E in one of three scopes: in the *default scope*, occurrences of E by any of T's transactions are reported; in the *until-success scope*, only occurrences of E by T's current *logical* transaction are reported; and, in the *transaction scope*, only occurrences of E by T's current *physical* transaction are reported. Monitoring of E is automatically canceled when a thread exits the monitoring scope, without stopping the debugged process.

Here are some usage examples. Once the debugger has stopped inside a transaction, we can resume execution and stop again if and when the debugged transaction aborts (monitoring TxAbort in transactional scope). Or, by using both monitoring parameters and scopes, we can stop if the logical transaction aborts involuntarily (monitoring TxAbort for any reason but self-abort in the until-success scope). Scopes are useful also within the debugger itself. For example by monitoring TxAbort in transactional scope, the debugger can notify the user if the debugged transaction is aborted when leaving the lexical scope by “stepping up” from a function to its caller.

In the future, scopes could be combined with additional support to allow placing monitoring commands *in the user program* to provide powerful debugging capabilities. For example, if we want to stop only if an execution of a given atomic block aborts, we can add a command to monitor TxAbort in the current thread, until-success scope, at the beginning of that atomic block. We can further narrow the monitoring by restricting the reason for the abort (which is a monitoring parameter of the TxAbort event). We can provide delayed breakpoints (Section 2.4.5): stopping when and if a transaction that executed a given instruction commits, instead of when the instruction is executed. This is done by adding a command to monitor TxCommit for the current thread in transactional scope right after the instruction in the program code. (We use the transactional scope rather than the until-success scope because if the transaction is aborted the instruction may not be executed again when the transaction is retried.) We can also support assertions, tests that an atomic block does not violate an invariant, by asserting the invariant inside the atomic block, and if violated, execute a command to monitor TxCommit for the current thread in transactional scope. The invariant is evaluated as part of the transaction, and is thus consistent with the committed transaction’s view of the data.

While the functionality of changing the user code to include such monitoring commands may not be available in most commercial debuggers today, we hope that by supporting scopes we will allow quick development of advanced debugging features (like delayed breakpoints) when and if this functionality becomes available, and maybe encourage its development.

3.3 Debugging Infrastructure Design

In this section, we describe how we designed the tm_db library to provide debuggers with a TM-independent interface for transactional debugging, and TM runtime designers with a simple, well-defined interface for transactional debugging support. Here we only focus on the high level design guidelines of tm_db; A full description of the library's API is available at: http://www.cs.brown.edu/people/levyossi/Debugging/libtmdb.pdf.

3.3.1 Overview

Two processes are involved in debugging a program: the *debugger* process, which runs the debugger code, and the *target* process, which runs the executable being debugged. These processes run in different spaces: the debugger cannot simply access variables and addresses in the target space through pointers, but must rather use some kind of inter-process communication.

Many debuggers export the ability to access the target process space via the proc_service interface, defined as part of OpenSolaris^{TM} [34]. This interface provides basic accessibility to a process's space, including the ability to look up symbols (e.g. finding the address of a global variable), and to read and write memory and registers.

The proc_service (or a similar) interface is implemented by debuggers such as dbx, TotalView®, and gdb to provide external libraries, like libthread_db and librtld_db , the ability to access the target process. In this way, the debugger can out-source the implementation of some debugging functionality to external helper libraries.

3.3.2 Design

Figure 3.5 shows the structure of our solution.

We implemented tm_db as an external helper library that lives in the debugger process space, and provides the debugger with the functionality described earlier. It uses the proc_service interface for

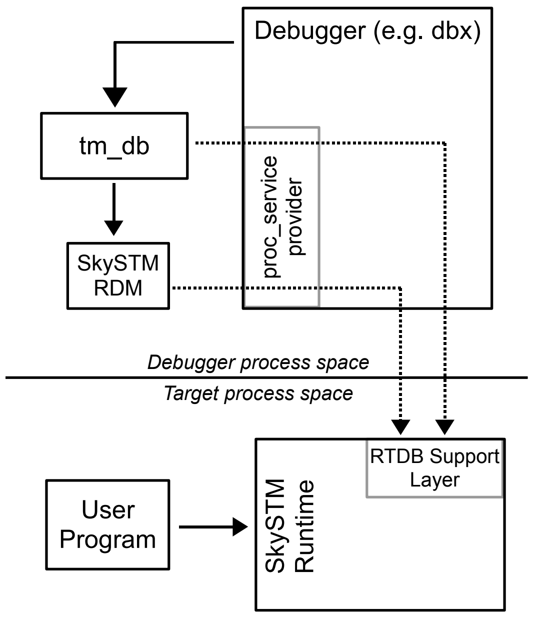


Figure 3.5: Debugging with tm_db

access to the target process, similarly to other external debugger helper libraries, such as libthread_db for functionality related to threads, and librtld_db for functionality related to the run-time linker. Our library can thus be used by any debugger that implements a proc_service provider.

A *Remote Debugging Module* (RDM) is the part of the debugging solution that depends on the particular TM runtime. Each TM runtime that supports debugging provides its own RDM that lives in the debugger process space, and accesses the target space through the proc_service interface to provide debugging support for that particular TM runtime. When the debugger starts debugging a program, tm_db accesses the debugged process to determine whether the program is using a TM runtime that supports debugging, and if so, to dynamically load the appropriate RDM. The RDM provides TM designers a well-defined interface for providing debugging support for their TM.

So far, we have implemented eight RDMs, to support debugging of transactional programs that use one of eight variants of the SkySTM runtime: easy versus lazy conflict detection, visible versus invisible reads, and privatization enabled or disabled. These RDMs are open-source to help other

TM runtime designers provide their own RDMs.[9]

Finally, in the target process space, the TM runtime is augmented with a *runtime debugging* (RTDB) support layer. This layer has two purposes. First, when a program is loaded, it indicates to tm_db which RDM to load. Second, once an RDM is loaded, it provides the information and functionality required to implement the various debugging features. For example, the RDM configures the RTDB support layer with which transactional events to track, and the RTDB support layer is responsible for the runtime filtering and event reporting, and so on.

Discussion

The tm_db library is really a proxy between the debugger and the RDMs. This additional layer allows us to simplify the RDM implementation by moving common functionality to tm_db. For example, as we describe in Section 3.4, SkySTM's RDMs are stateless: they do not store any information about the TM runtime, debugging session, and so on. In addition, we can move functionality between the debugger and tm_db without affecting all the RDMs. Having the debugger interface to a single module instead of many RDMs should make it easer to deliver and maintain the RDMs as part of the TM runtimes they support.

Note that the main reason for having a TM dependent component in the debugger process space is that the proc_service provider only allows basic access functionality to the debugged process. If, for example, it was easy for tm_db to call functions of modules in the debugged process space, then we could have united the RDM and the RTDB functionality into a new united component (living in the debugged process space), and have tm_db communicate with this new component using a TM independent API. But since proc_service only provides low-level communication functionality (mostly reading and writing memory and registers of the debugged process), our design splits the TM specific functionality between two modules — one that lives in the debugged process space (the RTDB layer), and one that lives in the debugger process space. The RDM is thus simply an agent

[9] See http://www.cs.brown.edu/~levyossi/Thesis/ and Chapter 5 for details.

of the TM runtime that lives in the debugger process space, allowing tm_db to use a simple, function based API when querying the TM runtime for debugging information. Therefore, while our design defines the interface between the debugger and tm_db, and between tm_db and the RDM, it does not constrain the interface between the RDM and the RTDB, nor does it dictate how the functionality should be split between the two modules. The TM designer is in the best position to pick the right balance between overhead to the runtime and complexity of the RDM.

3.3.3 Supporting Partial Functionality

Not all TM runtimes can support all the debugging features described in Section 3.2. For example, many STMs, including SkySTM [20], do not keep track of the exact addresses read by a transaction. With these runtimes, we cannot check whether an address was accessed by a transaction, but we may still be able to check whether that address is covered. As another example, the TL2 STM provides an optimization with which read-only transactions do not keep *any* information about their transactional reads. For these transactions, even read coverage information is not available.

A more interesting example is that of STM runtimes that may not be able to determine whether some transactions have already committed. These STM runtimes typically do not lock their read set and thus cannot guarantee that the locations they have read are not modified while attempting to commit. Instead, when trying to commit, a transaction must *read-validate* its read set, checking that the locations it read have not changed since the start of the transaction. With such an STM, a transaction takes effect at the beginning of the read validation only if the read validation completes successfully. Thus, if a transaction is stopped during the read validation, it is undetermined whether it has already committed or not. While this may not matter when stopping at normal breakpoints, which are placed in user code and will thus never stop a thread during its read validation, this problem may arise when switching to another thread, that might be at an arbitrary point of a transaction execution.

To help dealing with such missing functionality, the RDM interface provides various error codes to allow an RDM implementation to indicate that a feature is not supported, either temporarily (for example, it cannot determine this transaction's status at this point), or permanently (it cannot report read values for transactions). Different debuggers may handle these error codes in different ways; for example, when stopping at a point when it is (temporarily) unknown whether a transaction has committed, some debuggers may choose not to expose this fact and instead step the thread to a safepoint where the status is known again. In addition, having error codes to support partial functionality allows TM designers to initially provide an RDM that only supports a particular subset of the debugging features, and add support for more features over time as found necessary.

3.3.4 The Import Interface

Our solution will be useful only if debuggers can use the library to provide appropriate commands for debugging transactional programs. As noted, preliminary transactional debugging support is already implemented in Sun Studio dbx using tm_db, and we expect it will be available to the public soon. Note, however, that the code interfacing tm_db inside dbx is not likely to be open source, and thus it will not be possible for researchers to change existing and add new debugging commands.

To address this issue, and to ease gradual integration of transactional debugging support, we provide some functionality using a special dbx interface, called the *Import Interface*. The Import Interface enables one to add new commands to dbx without changing and recompiling the dbx code. This is done by letting an external shared library register new commands and functions to implement them, and then importing the library into dbx using the dbx *import* command. Such an external library cannot access the dbx internals, but it can use other external libraries like tm_db, already loaded in dbx. Thus, using the Import interface, we can provide an additional module with tm_db that will be imported into dbx and provide some additional, experimental debugging features. Such a module can be open source, and thus allow researchers to experiment with modifications or addition of new debugging commands, and provide an example for the designers of other debuggers of how to use the tm_db library.

3.4 Debugging support for an STM runtime

This section describes our experiences implementing RDM and RTDB support layer for the SkySTM runtime. While these issues are interesting in and of themselves, they also shed light on what it might take to adapt other STMs.

3.4.1 Overview

In principle, writing an RDM is a simple matter of writing remote accessor functions for data stored by the TM runtime and the RTDB support layer. In particular, the RDM uses the proc_service interface to access the target process's memory. It can locate the (remote) addresses of global variables, read from these addresses, and thus trace pointers in the target process until it reaches its goal.

We designed the interface between the RDM and tm_db so that the RDM can be stateless. In particular, the RDM provides tm_db with the set of threads that can run transactions, and for each such a thread, it provides a TM-specific key, opaque to tm_db, that is passed back to the RDM when tm_db queries it for thread-specific information. For SkySTM, we set the key to be a pointer to (remote) thread-private metadata. This way, the RDM does not need to keep track of debugging sessions, because all such state resides in tm_db.

Overall, SkySTM supports all of the debugging features described in Section 3.2, except for the ability to iterate through a transaction's read set, or to test whether a particular address was read by it. (The read coverage test is still supported for all transactions.) This support is provided with minimal overhead to the TM runtime: even with a microbenchmark that consists of only very small transactions, the runtime overhead (when the debugger is not attached) is less than 5%.

3.4.2 Computing Logical Values

SkySTM, like many other STM runtimes [8], uses deferred updates, meaning that transactional updates to shared memory are buffered in a thread-local buffer, which is written back after the transaction commits. There is thus a window of time in which the physical values (in memory) of locations written by the transaction do no reflect their logical values. During this time, however, the transaction holds exclusive write ownership of these locations.

Therefore, to compute the logical value of a location L, the SkySTM RDM can use the following simple algorithm:

- If no committed transaction holds exclusive write ownership of L, return the contents of L.
- Otherwise, if T is the committed transaction holding write ownership, search T's write set for L. If found, return the value from the write set, possibly combined with the actual contents of L if T did not write all of L's bytes. If not found, T covers L but has not written it, so return the contents of L.

Finally, as noted in Section 3.3.3, it may not always be possible to determine whether the transaction that holds write ownership of L, has already committed. In that rare case, we simply return a *not currently available* error code.

In future releases, we may instead support some kind of *safe-point* mechanism, where the RDM advises the debugger when the transaction is in an "unstable state", and allows the debugger to step it through to a point where the transaction status is unambiguous. Furthermore, if the RDM can assume that the debugger will *always* step a thread to a safe point, many parts of its implementation would be significantly simplified. For the current version of the library, however, we did not make such assumptions, and wrote the RDM assuming that the debugged process may be stopped at any point.

3.4.3 Monitoring Events

Event monitoring and filtering in SkySTM is safe and efficient. Monitoring is done on a per-thread basis. Each thread keeps a bit-mask, called the *monitoring command*, indicating which events should be reported. Each combination of an event plus monitoring parameter value (such as "aborted due to invalid reads") has its own bit in the monitoring command.

When an event occurs, a fast-path check tests whether the monitoring command is all-zeros (true whenever monitoring is off, such as when no debugger is attached). Otherwise, the specific bit for the event is checked, and if on, the event is reported. An event is reported by calling an appropriate stub for the event – an empty function in the runtime that the debugger places a breakpoint on. The values for the reporting parameters are passed as arguments to the stub.

To support scopes, the runtime must turn off event monitoring on scope exit. To do that, we keep two additional bit-masks, one which indicates the bits of the monitoring command that should be cleared when the physical transaction ends, and one for those to be cleared when the logical transaction ends. Updating the monitoring command when a transaction ends is thus a simple matter of applying the appropriate bit-mask to the monitoring command, and is only done when some event is monitored in a non-default scope (i.e. one of the masks is non-zero).

3.5 Concluding Remarks

The tm_db library takes a first step toward providing systematic support for debugging transactional programs. It provides only the basic, essential features. We expect that experience debugging real transactional programs will lead to development of additional debugging features, built on top of the basic library.

For example, adding the watchpoints functionality described in Chapter 2 can assist in detecting an incorrect interaction between transactional and non-transactional access to a variable. With transactional watchpoints, the user can place a watchpoint on a variable that is supposed to only be accessed non-transactionally, asking the debugger to stop if and when a transaction accesses it. Moreover, in some cases the allowed access to a memory location may change at runtime from transactional to non-transactional when the program uses a privatization technique to make a particular memory chunk private, and then access it non-transactionally. In these cases, the user may want to dynamically enable a watchpoint on a location when it becomes private, in order to detect a faulty program logic that results in a transactional access to a private location (which may be accessed non-transactionally at the same time). The ability to dynamically enable and disable watchpoints can be provided, for example, by a debugging API that the user, or maybe even the debugger, can use in an atomic block to set a watchpoint on the privatized location.

Lessons Learned

To this point, we have had only preliminary debugging experience with tm_db, but we have already learned a few lessons about the properties STM runtimes should have to improve the debugging experience for their users.

First, we learned that supporting a read iterator that provides information about the locations read by a transaction would be extremely useful. Suppose, for example, that the user stops at the end of an atomic block that traversed a tree data structure. If the addresses read by the transaction are known, users will be able to examine the tree in the debugger, while the debugger is showing which nodes of the tree were accessed. In other words, users will be able to reconstruct the traversal done by the transaction even though they only stopped at the end of it. Moreover, with the combination of logical and tentative values, the user will be able to see exactly what changes the transaction has done to the tree.

A second lesson that we learned is that when the user stops inside the atomic block, unless the transaction is in Invalid state and can no longer commit successfully, the logical value of all locations the transaction has read should match the value observed by the transaction. This property will make it much easier for users to reason about the state of the program that relates to the execution of the atomic block, as they would be able to examine any variables accessed by the atomic block and see the values that were read. If the transaction is in Invalid state, the values of the variables is less important because the transaction will have no effect, and the user can step through the re-execution of the atomic block that will follow.

Note that some STM algorithms do not guarantee this property of having the logical values match the values observed by the transaction as long as it can commit successfully. For example, some STM runtimes support an optimization that makes read only transactions seem to take effect at the time of their first read operation [8], before some of the atomic block's statements are executed. With this optimization the user may stop at a point in which the values observed by the transaction are no longer consistent with the current memory state (as reflected by the logical values), but the transaction may still commit successfully as long as the observed values are consistent with the state of the memory at the point of the transaction's first read. Moreover, this optimization makes it impossible to determine whether the transaction has already committed at the time of its first read until the atomic block execution is over. Therefore, users may not know whether the transaction has already committed when stopping inside an atomic block, or be able to rely on the values of variables they examine being consistent with those seen by the transaction.

We hope that these and future lessons learned when using the tm_db library will help TM runtime designers to keep the debugability of their system in mind when considering various STM algorithms and optimizations.

Higher Level Debugging Support

It is important to note that even though the tm_db library exposes many details on the transactions in the system, in some cases this information may only be used by the debugger and not exposed to the user.

For example, the debugger can easily step over the execution of an atomic block by tracing the TxCommit and TxAbort transactional events. Because tm_db provides information about the latest transaction of each thread even after it is completed, users may still be able to see various information about the atomic block's execution, such as its read and write sets.

As another example, some users may not care about physical vs. logical transactions; after all, from the user's point of view, there is only one transaction that matters in each execution of an atomic block: the one that commits it successfully. The debugger can avoid stopping at a breakpoint if it finds out that the physical transaction is Invalid or Aborted, or even keep stepping the thread in isolation throughout the retrying transaction, and stop at the breakpoint if and when it is hit again by the retrying transaction. The debugger can avoid retrying the transaction forever by examining the IsWaiting information to verify that the debugged transaction is not blocked by another transaction. If it is blocked, and the address for which it is waiting is available, the debugger can use the coverage information to find out the set of threads that cover the address, and step them to completion. With such a debugging functionality, users may not care to see the physical transaction index in the transaction ID, as any transaction they will ever stop at could be uniquely identified by the thread id and the logical transaction index.

We believe that the relatively low level interface of tm_db will provide debuggers the flexibility of supporting both high and low level debugging experience.

Chapter 4

T-PASS: A Profiler for Transactional Programs

T-PASS (Transactional Program Analysis System) is a profiling system for transactional programs. It is intended to help improving and better designing transactional programs, as well as the transactional memory runtimes that support them. We describe the profiling system's functionality, and the rationale for its design. T-PASS is designed to work with the SkySTM runtime, which can be configured to run a range of conflict detection and contention management strategies. T-PASS can also be integrated with a transaction-aware debugger. We describe a novel technique for exploiting the TM runtime to replay profiled transactions, including aborted transactions. We believe that T-PASS demonstrates that transactional programs can be profiled more easily and more effectively than programs based on locks and conditions.

4.1 Introduction

In this chapter we shift the focus from debugging to profiling of transactional programs. Unlike debugging, which focuses on fixing problems in the program that may result in incorrect behavior, the purpose of profiling is to understand and improve the *performance* of the program. While Transactional memory (TM) promises to make writing scalable multithreaded programs easier, it is clear that even with TM it is still a challenge to design and implement scalable concurrent algorithms. Making algorithms scalable often requires a detailed understanding of how the program is structured, and how different parts of the program interact.

Indeed, there has been significant interest recently in good profiling tools for transactional programs, even more than for a debugging tool. The reason for this is that many transactional programs were converted from lock-based programs by simply replacing critical sections with atomic blocks. In such cases, assuming that the original lock-based program is correct, there is usually no need for intensive debugging to get a correct transactional program. However, because the critical sections were never designed to run concurrently, they often share data unnecessarily, resulting in a non-scalable transactional program that performs poorly.

We claim that the structured nature of TM makes performance profiling easier than with conventional synchronization. Because the TM runtime manages synchronization, it is possible to track runtime conflicts and dependencies in a much finer granularity than that of the atomic blocks in the program. A good profiling tool encourages a methodology in which the programmer starts with a *simple and correct* coarse-grained solution, and successively refines it in response to performance bottlenecks revealed by profiling. Profiling makes it possible to focus efforts on those parts of the program that would benefit from refinement, without wasting resources on those that would not.

Here are some simple ways in which a profiler can help tune performance for transactional programs:

- To reduce conflicts, the programmer might consider breaking large atomic blocks into smaller blocks. Profiling can help decide when it is worthwhile to do so.

- To reduce synchronization overhead, the program may *privatize* data by rendering it inaccessible to other threads [35], and then process the data without synchronization. When processing is complete, it could make that data accessible again. Profiling can help distinguish when privatization would enhance performance and when it would not.
- Many TM systems are subject to *false conflicts*: data items that are logically distinct may be treated by the TM runtime as a single synchronization unit. Profiling can detect which false conflicts affect performance, and help fixing them.
- Some TM runtimes can be configured in different ways [20], by detecting conflicts eagerly or lazily, or choosing different contention management policies. Profiling tools can help to choose the best way to configure a TM runtime for a given application.

In addition, because TM is still an open research area, profiling information can help improving not only particular transactional programs, but also the TM runtimes and compilers that support them. As noted, there are many different STM algorithms, and it is not clear that there is a single algorithm that will fit best the needs of all transactional programs. Profiling information can address questions such as when it makes sense to detect conflicts eagerly and when lazily, and help build TM runtimes and compilers that better adjust to the transactional program that they are running.

The T-PASS Prototype

We present T-PASS (Transactional Program Analysis System), a prototype system for profiling transactional programs. We describe the system's functionality, and the rationale for its design. T-PASS is developed to work with the SkySTM runtime [20], a software transactional memory system that can run a range of conflict detection and contention management policies. T-PASS uses the Dynamic Tracing framework provided by DTrace [1] to collect and aggregate the profiled data, together with a sampling mechanism to reduce profiling overhead. Preliminary experiments suggest that in the worst case, for programs that consist entirely of transactions, T-PASS imposes a low overhead: about 3-4% when the profiler is not attached, and about 10% when the profiler is attached and profiling data is collected.

T-PASS collects data in four categories. First, it captures basic information from single-threaded runs, such as: How many transactions were executed for each atomic block? How much time was spent in each atomic block? How large was each transaction's data footprint?

Second, it captures the cost of contention in multi-threaded runs, such as: How much time was spent doing useful work in committed transactions, and how much was contention overhead, such as time executing aborted transactions, or waiting for other transactions? How long did each atomic block take in the presence of contention? How many times did it retry?

Third, it provides data to analyze conflicts, such as: Which accesses (instructions) caused contention by forcing transactions either to abort or to wait? Which sets of locations conflicted with each other? Which instructions accessed these locations? Identifying contending instructions and locations helps distinguish true conflicts from false ones.

Finally, because of the different nature of transactional programs, some memory accesses may induce unnecessary high overhead, and even impede scalability (for example, a transactional write that does not change the value of the written object). T-PASS helps to identify these memory accesses and provide guidance for how (and whether) to avoid their high overhead.

T-PASS encompasses a Java$^{\text{TM}}$ front-end for displaying and navigating the collected data. We support many queries, such as which atomic blocks formed the longest transactions, or which accessed the largest data set. Is the total time spent executing a particular atomic block dominated by a few long transactions? There are many other possible queries.

Another interesting direction that we explore is how debugging and profiling can be combined to provide further information to the programmer. For example, one could use the profiler to identify the longest-running transactions, and examine them with the debugger. T-PASS supports this feature, allowing the programmer to specify conditions on the profiled data under which the program should be stopped and examined with a debugger. Furthermore, we present a new technique that allows the debugger to replay the profiled transaction to examine its step-by-step execution.

The rest of the chapter is organized as follows. Section 4.2 introduces basic concepts and terminology. Section 4.3 describes the profiling information that T-PASS provides, demonstrates how it is presented to the user, and provides examples for how it may be used when optimizing a transactional program. In Section 4.4 we describe the system's design, and In Section 4.5 we explain how T-PASS can be used with a debugger, and how to provide the replay functionality for profiled transactions.

4.2 Basic Concepts and Terminology

Data and Metadata

As noted, TM runtime systems typically control access to user-level data items with *metadata*, which we call *ownership records* [5]. Multiple data items are often controlled by the same ownership record. In general, the coarser the mapping between data and ownership records, the less overhead to manage the transaction's access information, but the higher the likelihood there will be false conflicts, which may hurt scalability.

The mapping between data and ownership records is internal to the TM runtime implementation, and typically not part of the programming model. Nevertheless, because of the aforementioned trade-off between the TM mechanism overhead and the scalability that it provides, and because of the need to identify false conflicts, effective profiling requires basic information about this mapping, such as whether two data items are controlled by the same metadata, or the ratio between the number of data and metadata items accessed.

Atomic Blocks, Logical and Physical Transactions

As described in Section 3.2, we identify transactions in three levels: the atomic block level, the logical transaction level, and the physical transaction level.

All three levels are useful for profiling. At the atomic block level, it is useful to know how many times each one was executed, how much time was spent in each atomic block, and how big was the data set accessed by transactions of each block. For each logical transaction, it is useful to know how many physical transactions it took to execute it, how long the execution was, and how that length compares to that of the last physical transaction that completed it. For each physical transaction, it is useful to know how many physical transactions have failed due to a conflict on a particular set of addresses, and how much time was lost by these conflicts (the duration of the failed physical transactions and the time spent waiting for other transactions). T-PASS provides information in all three levels, and a wide range of queries to correlate between them.

Sampling and Filtering

To keep the profiling overhead down, and to perturb the transaction interleaving as little as possible, we profile only a small fraction of the transactions, chosen uniformly at random from either the physical or the logical transactions. We note that a uniform sample of the logical transactions can be obtained from a uniform sample of the physical transactions by dropping the failed physical transactions from the sample (as each logical transaction has exactly one successful physical transaction). When using this method, however, we only see the information reported by the last physical transaction of each logical transaction in the obtained sample.

To make sense out of the data collected, T-PASS provides a front-end with the ability to further narrow the sampled data, and to run sophisticated queries against it. For example, the front-end can be configured to show only the distribution of logical transaction sizes for a particular atomic block. The results can be further filtered to show only the data for logical transactions whose execution time is longer than a particular value, or for logical transactions that exceeded a certain number of retries. In the next section we describe in detail what data T-PASS presents to the user, and the filtering functionality that can be applied to it.

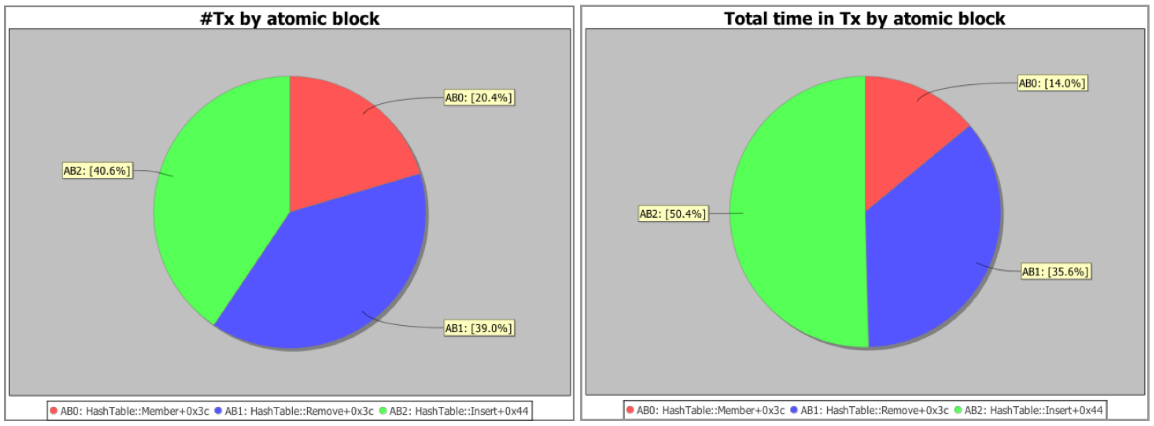


Figure 4.1: Number of executions and total time for atomic blocks

4.3 What to Profile

T-PASS organizes the displayed data into four categories. Here we describe each category, and the queries and filtering features that they support. All graphs presented here are snapshots from the profiling front-end. Due to the dynamic nature of our prototype, we were limited to showing only a few examples. More detailed examples are available in demo videos at:

http://www.cs.brown.edu/people/levyossi/profiling.

4.3.1 Basic Characteristics

The first category encompassing information not directly related to concurrency, and is usually collected for an execution where transactions are not interfering with each other, for example like in a single threaded execution. The profiler collects basic information about each atomic block as it is executed, helping to identify performance bottlenecks such as long transactions that dominate the execution time, as well as transactions with a small data footprint that may be candidates for hardware acceleration on platforms that support hardware transactions of limited size [7].

The first two charts in the report for this category describe how many times each atomic block was executed, and how much time was spent in each. Figure 4.1 shows these charts for a single-thread execution of a small hash table program. Each atomic block corresponds to one of the table operations: Insert (), Remove(), or Member(), and has a section in the pie charts. We identify an atomic block by its first instruction, just like the tm_db library does. From this report we can deduce that on average, Insert () and Remove() operations take longer than Member() operations because the latter represents a smaller slice of the time distribution pie than in the transaction count pie.

The report also displays the distribution of transaction sizes. There are two metrics of interest: the number of unique locations accessed, and number of ownership records (metadata) acquired by the transaction for reading[1] and writing.

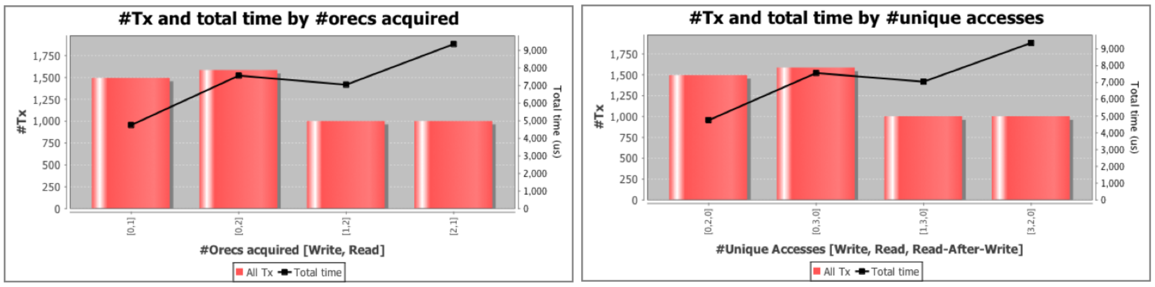


Figure 4.2: Distribution of transaction sizes

Figure 4.2 shows the transaction size distributions according to these two metrics. In both bar charts, each bar corresponds to a different size category. In the first chart, the categories are labeled with a pair of values $[W, R]$, denoting the number of ownership records that were acquired for writing and for reading. In the second chart, the categories are labeled with a triplet $[W, R, RAW]$ denoting the number of unique locations that were written (W), read (R), and read-after-written (RAW). We separate reads-after-writes from regular reads because many STM runtimes implement them differently, for example because of the need to look up the value in a write buffer when the deferred updates method is used.

[1]The SkySTM run-time [20] acquires ownership records for reads as well as for writes. While not all TM run-times do this, almost all pay an overhead proportional to the number of metadata items associated with a transaction's read set.

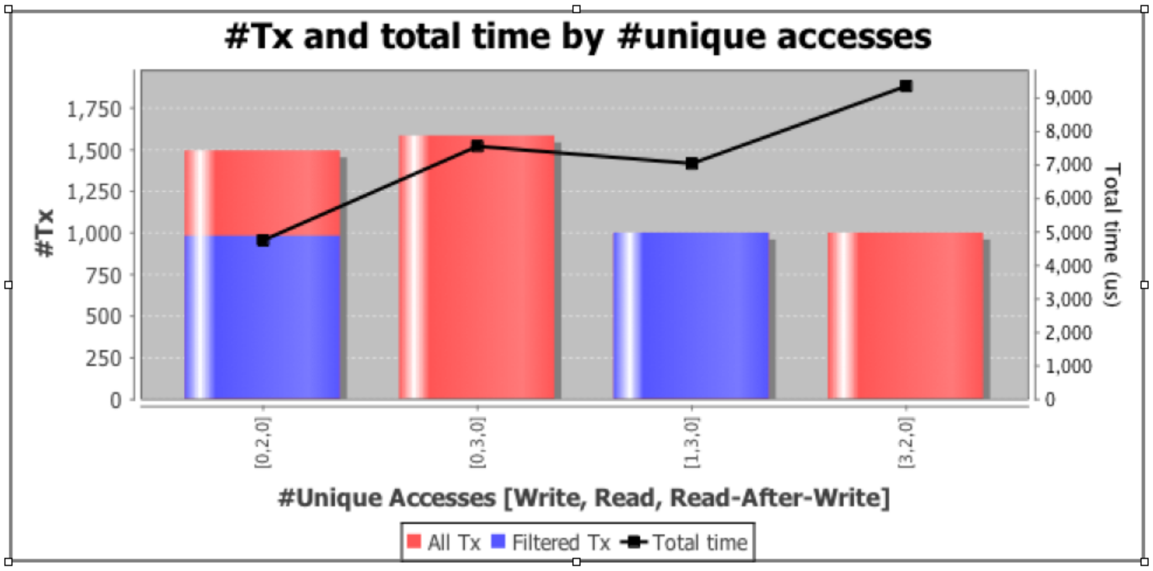


Figure 4.3: Distribution of transaction sizes filtered for an individual atomic block

The bar height shows how many transactions of each size were monitored. In addition, the graph also displays a curve showing the total time spent executing transactions of each size category. The Y values for this curve are presented on the right Y axis, while the values for the bars are presented on the left Y axis.

With the combination of the bar chart and the curve, the user to tell whether the bulk of the execution time was spent on a few large transactions, or on many small ones. This information is especially valuable for evaluating the potential benefit of running some of the program's transaction using HTM, which may only be capable of running transactions up to a certain size. In this example we can see that even though approximately 60% of the transactions were read-only (the first two bars in the chart), they only stand for less than 45% of the execution time: most of the execution time was spent on the larger, non read-only transactions.

To correlate the transaction size information to the user code, it is often necessary to see the distribution of transaction sizes for an individual atomic block. This information is accessible by

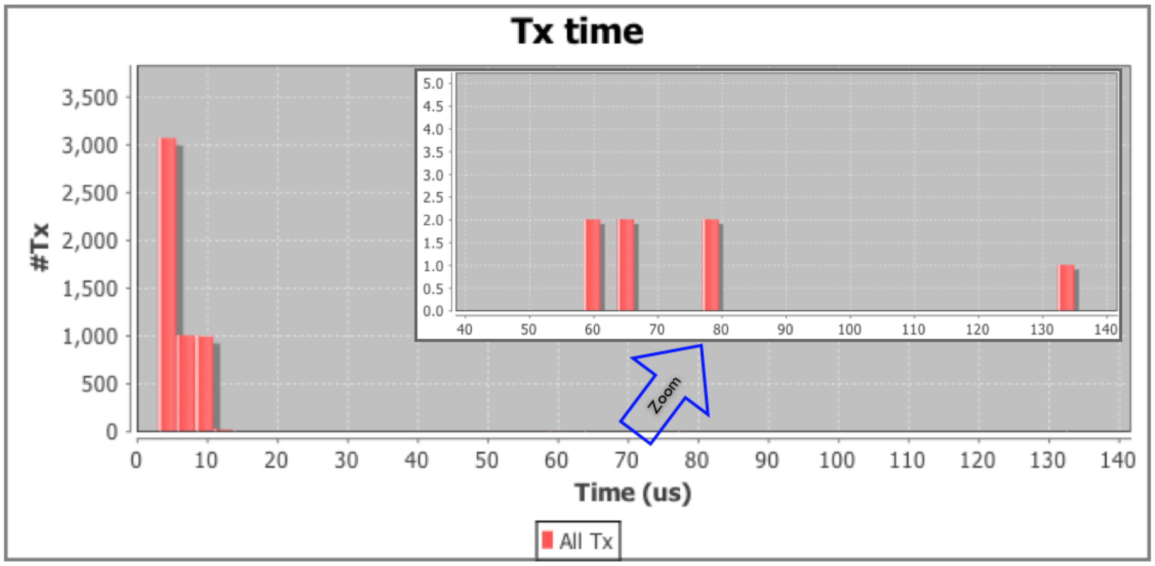


Figure 4.4: Distribution of transactions' execution times

filtering the data by an atomic block. For example, Figure 4.3 shows the transaction size distribution for the Remove() atomic block. The figure presents the same chart as in the right hand side of Figure 4.2, but with bars broken by color to show what fraction of each was contributed by transactions executing the Remove() atomic block (denoted as the "Filtered Tx" data series in the labels). In this example, we can see that about half of the Remove() transactions were read-only (reading two unique locations). This is because the hash table was initialized to contain half of the keys in the range, so removing a random key in that range has a 50% chance of not finding the key and leaving the table unmodified. The rest of the Remove() transactions wrote one location, and read three.

The last chart in this report, shown by Figure 4.4, presents the distribution of transactions' execution times. The figure shows that the vast majority of the transactions took less than 15μs, but a few took longer than 50μs. Once again, this information may be valuable to evaluate the potential benefit of using an HTM mechanism, as in some cases hardware transactions cannot survive a timer interrupt and are thus limited to a certain execution length. Like the transaction size graphs, the time graph can be filtered to focus on a particular atomic block.

While the most basic form of filtering is by atomic block, T-PASS supports many other kinds of queries. For example, one can ask to see only transactions of a particular size or execution time, by filtering by the corresponding bar in one of the bar charts; then one can see, for example, how transactions of this size or length are distributed between the different atomic blocks. Similarly, one can explore the relationship between the number of unique locations accessed and the number of ownership records acquired by filtering for a particular number of ownership records, and so on. The flexible filtering functionality can help the programmer pin down performance bottlenecks, and find out the reason for the high overhead paid for them.

We believe that the reports in this category are useful for understanding basic characteristics of the transactional program, and how it may be optimized. For example, if the execution time is dominated by very long and large transactions, the programmer may consider privatizing some of the data and accessing it non-transactionally; if an execution of a particular atomic block is dominated by transactions of a small size, then it may be worth using techniques like HyTM [5], PhTM [24] or TLE [6], which use best effort HTM when possible and resort to a software solution otherwise.

4.3.2 Contention Profiling

The second category concerns contention-related performance issues that arise when multiple concurrent threads access shared data. The report for this category represents data collected during a multithreaded run, and is presented in terms of logical transactions. As in the previous report, a pie chart shows how many logical transactions were profiled for each atomic block (not shown).

To see how much execution time was wasted on contention, the logical transaction's time is divided into three categories. *Failure time* is the duration between when the logical transaction began, and when its last (successful) physical transaction began. It shows the time spent on failed physical transactions, as well as any back-off time between them. *Wait time* is the time spent by the last physical transaction on *contention management*, that is, on waiting for other conflicting

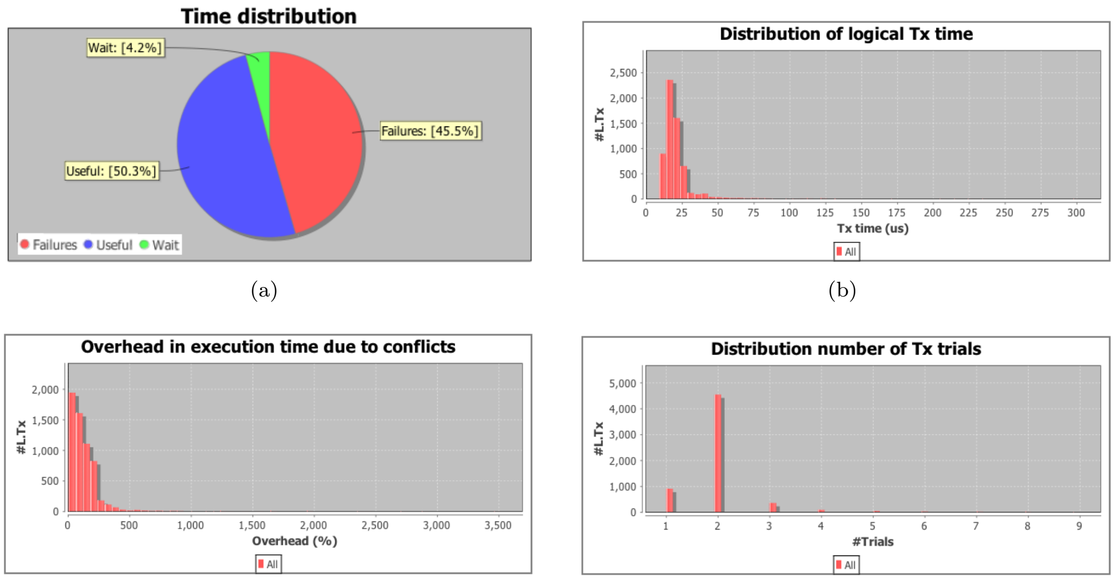


Figure 4.5: Contention profiling: Overall time distribution by category (a), Logical transaction time distribution (b), Contention overhead distribution (c) and Number of trials distribution (d).

transactions. Note that waiting by failed transactions is not included here, as it was already counted in failure time. *Useful time* is everything else: that is, the time spent by the last, successful physical transaction minus the time it spent on contention management. We define the *contention overhead* for a logical transaction to be:

$$\frac{\textit{failure time} + \textit{wait time}}{\textit{useful time}}$$

Figure 4.5 shows a summary report for contention profiling. Part (a) shows a pie chart with the overall time distribution of the profiled logical transactions, divided into the three categories defined above. This particular example shows a highly-contended execution of the hash table micro-benchmark. From this pie chart we can see that the average contention overhead, as defined above, is approximately 100%, with 90% of it spent on failures rather than on waiting. This is because the default contention management policy used with the SkySTM run-time never makes writers wait for conflicting readers; also, because we are using lazy conflict detection, writers hold ownership for a very short duration, implying also that waiting time is very short.

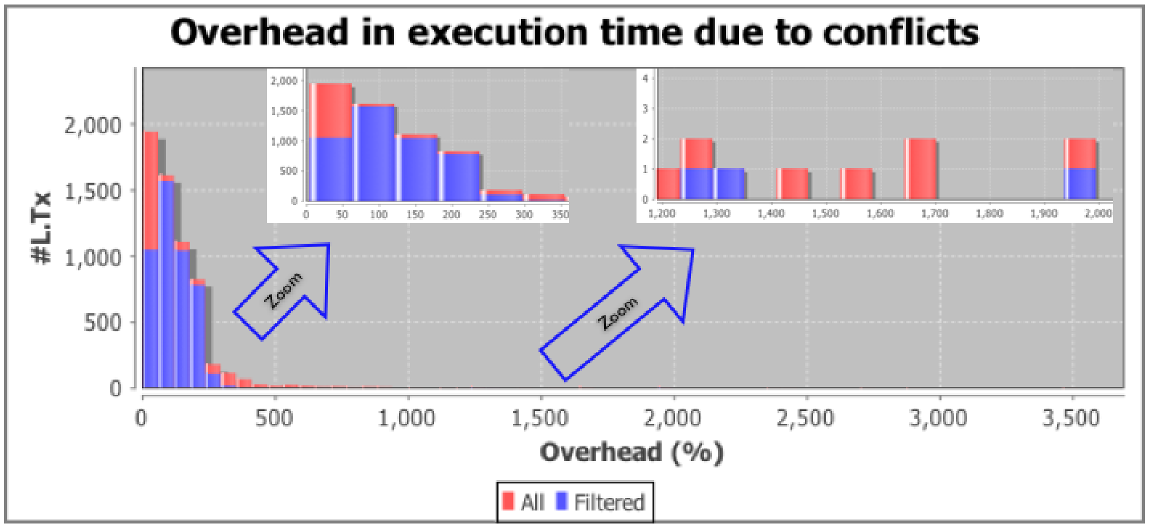


Figure 4.6: Overhead distribution filtered for transactions with two trials

Parts (b), (c), and (d) show three distributions, each giving a different view of the profiled logical transactions. Part (b) shows the distribution by execution time, Part (c) by contention overhead, and Part (d) by the number of physical transactions (trials) behind each logical transaction.

These three distributions are quite correlated, but each can be useful in a different way. For this reason, we support filtering by any one of the bars in these bar charts, answering queries such as the distribution of overheads for a given logical transaction length, or how much of a given overhead value is attributed to waiting and how much to failures. This allows identifying interesting outliers, like the one in Figure 4.6, which shows the overhead distribution for transactions with two trials: the overhead of the vast majority of the filtered logical transactions is indeed centered around 100% (as expected for a transaction that had 2 trials), but there were also a very few transactions that experienced an overhead of more than 1900%. In Section 4.5 we further investigate this observation using the debugger.

Filtering can also be useful to correlate the contention overhead with the actual time wasted on contention: a low contention overhead value for a long transaction may incur more cost than a higher contention overhead for a short transaction. Finally, as for the previous category, we can also filter for a particular atomic block, or apply multiple filters to further narrow the data being shown.

4.3.3 Conflicts Analysis

While the second category focused on the program behavior under contention, the third *conflicts analysis* category focuses on the conflicts causing the contention.

Two accesses conflict when the TM run-time maps them to the same ownership record, and at least one access is a write. A *false conflict* occurs when the conflicting accesses actually address distinct variables that conflict only because they have been assigned to the same ownership record.

Each reported conflict has an associated set of read and write accesses executed by the reporting transaction, which maps to the ownership record on which the conflict occurred. We group all conflicting accesses by ownership record, each identifying a *conflict set.* Each individual access is identified by the instruction that executed it, showing the user, for each conflict set, which user-level instructions executed the conflicting accesses. The user can distinguish false from true conflicts by checking whether these accesses are for the same variable.

Next we define the *cost* of a conflict. We say that a transaction *won* a conflict if that conflict did not force it to abort (either because it aborted its rival transaction, or because it waited for the rival to finish), and that the transaction *lost* the conflict if the conflict caused it to abort. If the transaction loses a conflict, then the conflict cost is the physical transaction time, because the transaction must be retried and that time is lost. If the transaction won, then the cost is the time it waited for its rival (which may be zero).

Note, however, that it is not always possible to assign blame to a specific conflict when a transaction aborts. For example, a transaction may read from several data items, and later discover that some of them have been modified. When this occurs, we divide the cost (that is, the physical transaction time) equally among all conflicted ownership records. Dividing the cost (instead of charging the full cost to each) makes sense for two reasons. First, we want the cost to be additive: the cost over all conflicts should sum to the total amount of time spent on conflicts by all the profiled

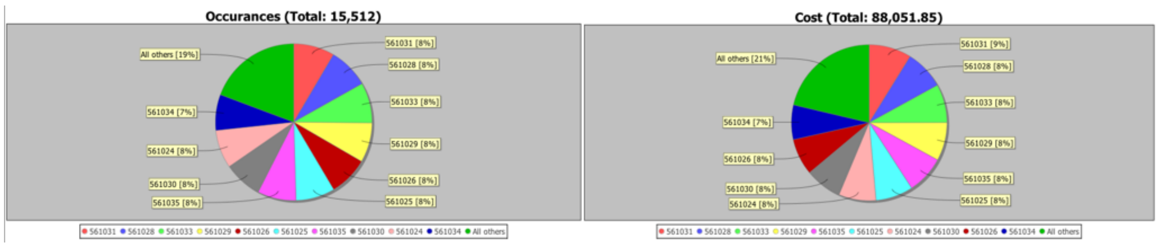


Figure 4.7: Number of conflicts and their costs for each conflict set.

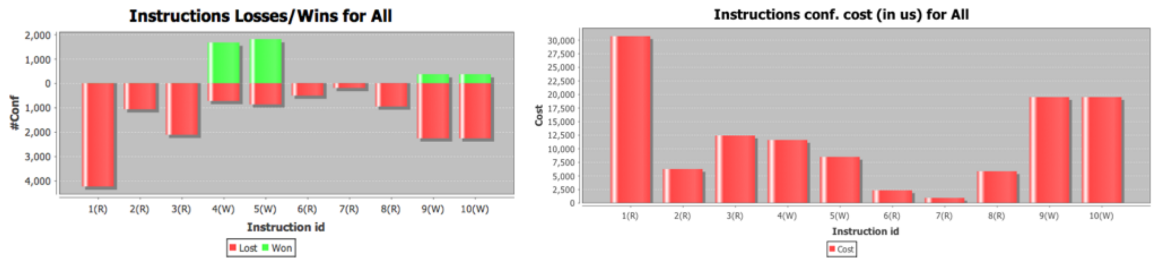


Figure 4.8: Instruction conflict losses and wins (left), and conflict costs by instruction (right).

transactions. Second, we want to assign a greater weight to conflicts that were the only reason for a transaction to abort, because resolving these conflicts is more likely to lead to performance improvements.

To evaluate a conflict set, we look at two factors: the number of conflicts that occurred in each conflict set, and the total cost of these conflicts. This is shown by the pie charts in Figure 4.7. The pie chart sections, each corresponding to a different conflict set, are sorted by size to help the user see whether a particular conflict set encompasses most of the conflicts, or dominates the contention cost.[2]

To relate the conflicts to the accesses causing them, T-PASS provides the two additional charts in Figure 4.8, with information on the actual accesses in the various conflict sets. In both charts, each bar corresponds to a particular user-code read or write operation. For brevity, the X axis shows only sequence numbers for these operations, and whether they are reads or writes; A separate table

[2] The conflict sets' labels are unique IDs that internally identify the orec on which the conflict occurred; they may be used in future debugging support.

(not shown) identifies the exact accessing instructions.

The first chart in Figure 4.8 shows, for each access, how many conflicts it won (the green bar above the zero value), and how many it lost (the red bar below the zero value). This chart shows which reads or writes are usually winners, probably causing other transactions to abort. In this example, writes almost always win, and reads almost always lose. This asymmetry is a result of the particular contention management policy used for this benchmark, in which writers immediately abort conflicting readers, and readers almost never abort conflicting writers.

The second chart shows the conflict cost distribution among all accesses. That is, the bar for each access shows the total cost of all conflicts involving that access. This chart is essential for identifying *instructions* that cause contention. In this example, even though Figure 4.7 shows that most of the conflicts' cost is pretty evenly spread among ten different conflict sets, there is one particular instruction (leftmost bar in the chart) that has a significantly higher cost assigned to it than to others. Checking the identity of this instruction we saw that it corresponds to reading the pointer to one of the hash table buckets. Since our hash table had ten different active buckets, each mapping to a different ownership record, these conflicts appeared in ten different conflict sets, but they were all caused by the same scenario: many threads access some bucket for reading, and one modifies the bucket when inserting or removing an element. (The investigation of this scenario is demonstrated in more detail in the "Conflicts Analysis" demo video at: `http://www.cs.brown.edu/people/levyossi/profiling`.)

It would have been difficult to identify this bottleneck looking only at the charts of Figure 4.7, which focus on bottlenecks in the data domain. On the other hand, conflicts caused by multiple instructions that accesses the same data item would show up clearly in the charts of Figure 4.7, but not in those of Figure 4.8. The combination of the charts in these two figures helps the user identify contention bottlenecks in both the data and the instruction domains.

Finally, while Figure 4.8 in this example shows *all* conflicting accesses, the user can easily identify the accesses of a particular conflict set by filtering the data, seeing which accesses are conflicting with each other. This is especially important in the presence of false conflicts, where accesses to different variables may still conflict.

Contention Management

Profiling information can be critical for evaluating the effectiveness of the contention manager (CM). This is important for a couple of reasons. First, TM runtimes are still an open research area; information about the effectiveness of their CM strategies can help improve TM runtimes, making them fit better to the needs of real transactional programs. Second, some TM runtimes [20] provide a configurable CM component, allowing different programs to pick different CM strategies. In these cases, the profiler can help the programmer pick the right CM strategy for the program.

Figure 4.9 shows additional information intended to help evaluate the effectiveness of the contention management strategy. In this example we show the information accumulated over all conflicts, but information can be filtered to show only a particular conflict set.

The figure shows three pie charts. The first (top) chart shows how many conflicts were lost, how many were won without waiting for the rival transaction(s), and how many were won after waiting. The labels for each section show the following information. The average abort-other (AvAO) metric shows the ratio between the number of conflicts in each category, and the number of times they caused aborting other transactions. We note that because of read sharing, this number is a lower bound on the number of transactions that were aborted due to these conflicts, because a writer often aborts all readers it conflicts with without knowing how many such readers there are. In this example, we see that even though most conflicts were won without waiting, waiting significantly reduced the need to abort other transactions (conflicts in the WonNoWait category resulted in 1.5 times more abort-other operations than conflicts in the WonWait category). In addition, for the WonWait category, the label also shows the average waiting cost, and its relative fraction of the physical transaction time. In this example, waiting accounts for only a small fraction (12%) of the transaction time.

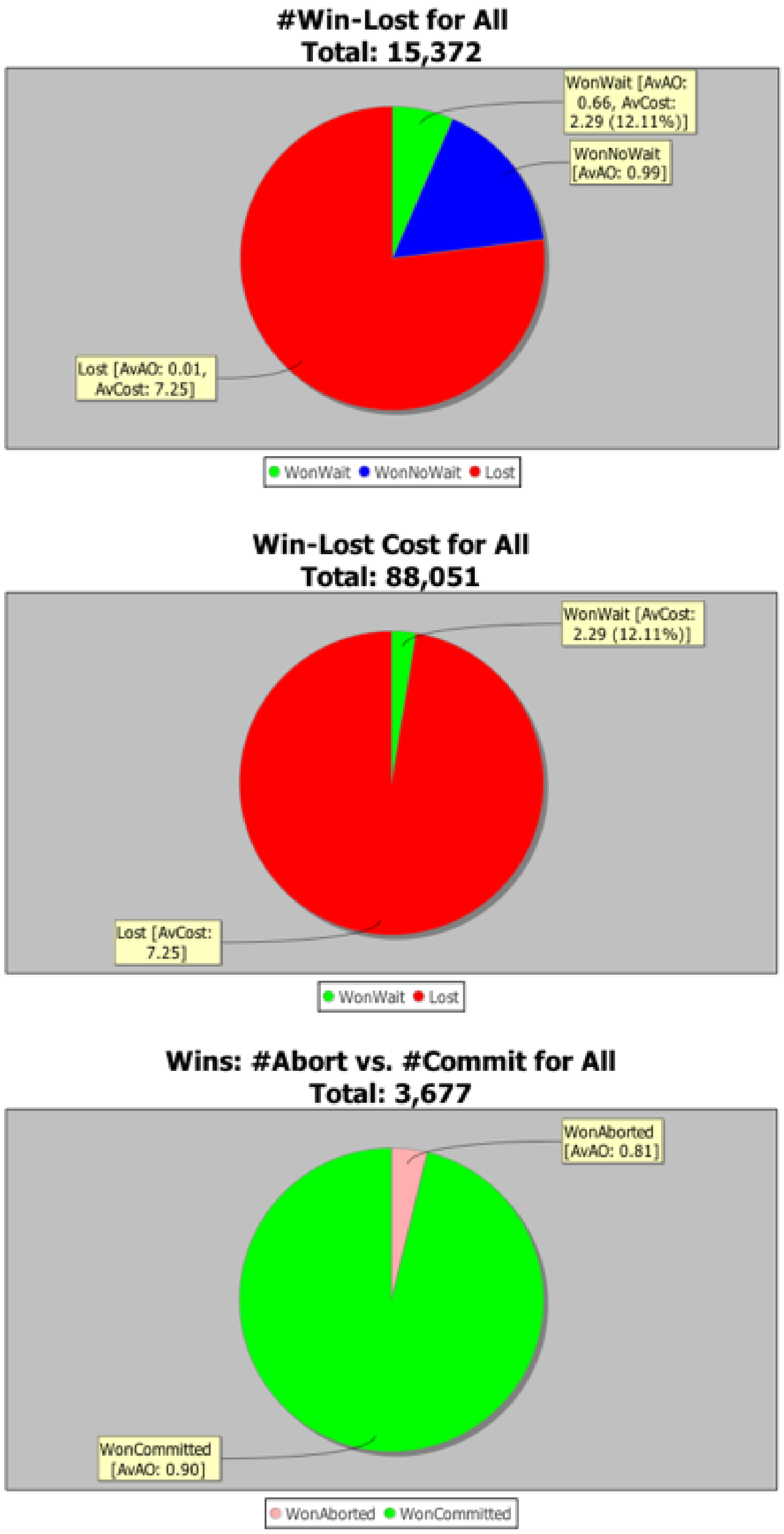


Figure 4.9: Contention management information.

The second pie chart shows how cost is distributed between won and lost conflicts. (Conflicts that win without waiting have zero cost, and do not appear.) The figure shows that the cost is mostly due to lost conflicts, not to waiting. In particular, the average conflict cost for lost conflicts is significantly higher than that for won conflicts. This makes sense because the previous chart suggests that waiting accounts for only a small fraction of the transaction time, while losing a conflict requires rerunning the entire transaction. The combination of these two charts suggests that waiting more often before aborting the rival transaction(s) may help reducing the overall contention cost, as it is likely to reduce the number of aborted transactions with a relatively low waiting cost.

The last (bottom) pie chart shows how many of the conflicts that were won were then followed by a successful commit, and how many of them were followed by an abort. A conflict that was won by a transaction that eventually aborts may have caused other transactions to abort unnecessarily. In this example, almost all conflicts that were won were followed by a successful commit. This observation is not surprising because transactions in our example are short and have few writes; Because readers rarely win a conflict, and because the TM run-time uses lazy conflict detection and acquires write ownership only when the transaction tries to commit, the window of vulnerability between winning a conflict and finishing the transaction is very short.

4.3.4 Identifying Special Accesses

Not all data accesses are created equal. The profiler can flag several kinds of accesses that might indicate unnecessary synchronization.

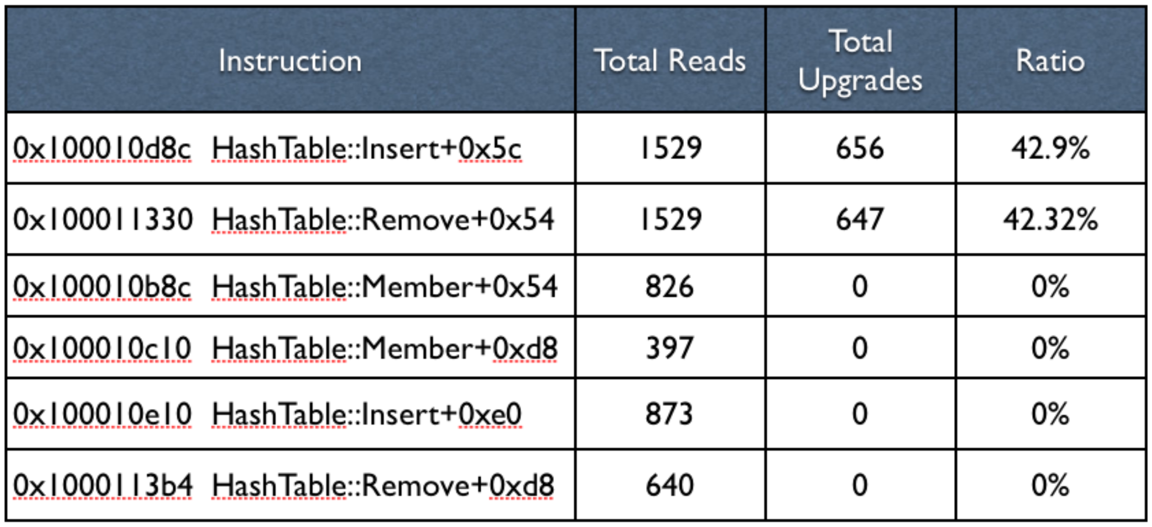
Write Upgrades

The first kind of flagged access is an *upgrade*, where a transaction acquires write ownership for a data item for which it already has read ownership. Recall the scenario we previously described where many threads read a pointer to a hash table bucket and then some tries to write it, aborting all other readers (Section 4.3.3). This scenario is a common source of contention in transactional programs.

Sometimes, when it is known that the read acquisition is always (or even usually) followed by a write acquisition, it makes sense to avoid this scenario by *promoting* the initial read acquisition to a write acquisition, preventing other transactions from sharing read ownership of data that will soon be written. Promoting the read to a write could also reduce synchronization overhead, as it replaces two acquisition operations with one. Some STM runtimes [20] already provides the API to support such a promotion, as they separate the functionality of asking for a read or read&write permission from the functionality of executing the actual transactional access. Thus, the programmer can ask for a read&write permission before executing the first read of the location. When a compiler is used to generate the code interfacing the TM runtime, the user may be able to ask for a write promotion by using a special syntax, or by directly calling a function in the TM runtime API.

In Figure 4.10, the profiler shows the user how many times each read access was executed, and how many times the associated read ownership was upgraded, suggesting which read accesses may be good candidates for promotion. It can then be useful to check which upgrades were responsible for conflicts. In this example, there are two accesses, one in Insert (), and one in Remove(), which are upgraded 40% of the time. These accesses are indeed the reads of a hash table bucket pointer that we previously described. (Recall that about 50% of the Insert () and Remove() operations fail and do not modify the table, which explains why the upgrade only occurred in less than 50% of the time.) Checking these accesses against the graphs in Figure 4.8, we notice that these accesses are responsible for a large fraction of the overall conflicts' cost, suggesting that promoting these reads to writes may help to avoid some unnecessary aborts.

Note that a particular user-code read access instruction may be executed multiple times by a single transaction, each time accessing different data items (for example, walking over a tree or linked list), where the transaction later upgrades only one of the data items. In this case the profiler counts multiple regular executions for the instruction, and only one upgrade. This is because marking this instruction as an access to be promoted will have the effect of preventing read sharing for all of the data items it accesses, even those that are never upgraded.



Instruction	Total Reads	Total Upgrades	Ratio
0x100010d8c HashTable::Insert+0x5c	1529	656	42.9%
0x100011330 HashTable::Remove+0x54	1529	647	42.32%
0x100010b8c HashTable::Member+0x54	826	0	0%
0x100010c10 HashTable::Member+0xd8	397	0	0%
0x100010e10 HashTable::Insert+0xe0	873	0	0%
0x1000113b4 HashTable::Remove+0xd8	640	0	0%

Figure 4.10: Output of write-upgrades analysis

Silent Writes

A second kind of flagged access is a *silent write*, one that does not change the data item's value. Such writes can cause unnecessary synchronization and contention overhead. For example, in a red-black tree, the root node is always colored black. In a sequential implementation, a thread rebalancing the tree does no harm by coloring the new root node black, even if that node is already black. In a transactional implementation, however, recoloring that node may force the transaction to acquire write ownership unnecessarily, introducing a gratuitous conflict with all other concurrent transactions. Instead, it makes sense to read the node's color, and to change it only if necessary.

In addition, since transactions group together multiple writes into one atomic operation, a silent write may be also caused by a series of writes that change a variable from value A to B, and then back to A. We denote these as *silent series*, as opposed to simple silent writes. For example, in the following code:

```
atomic {
  x = x*y;
  if (z != 0) x = x/z;
}
```

the value of variable x is not modified if y and z are equal and z is nonzero. The user can guarantee that any particular write is not silent by reading the value in the location to be written before writing it. In many cases avoiding certain silent series is also possible with a slightly higher overhead, like in the example above that can be re-written as:

```
atomic {
 if (y != z) {
    x = x * y;
    if (z != 0) x = x/z;
  } else if (z == 0) x = 0;
}
```

to avoid the silent write to x. In a more complex code, where x may undergo a long series of writes, the programmer may be able to cache the written values in a local variable (e.g. one that is stored on the stack or in a register) and only write the final value to x at the end of the transaction if that value differ from the current value of x:

```
atomic {
  int cached_x = x;
  // replace all access to x with accesses to cached_x
  ...
  if (x != cached_x) x = cached_x;
}
```

T-PASS detects writes, and series of writes, that are often silent, presenting the silent vs. non-sielnt ratio for each. In addition, note that eliminating a silent write will not always eliminate acquiring write ownership, because the transaction may have written to other data items controlled by the same ownership record. T-PASS takes this into account, reporting for each silent write (or silent series) how many times avoiding the write access would eliminate a write acquisition. This information, together with the conflicting accesses information in Figure 4.8, can guide the user to the instructions for which the overhead of avoiding the silent writes may be worthwhile.

Finally, note that silent writes could be prevented by the TM run-time, by testing whether a write is silent before acquiring the ownership record. Such tests, however, incur additional overhead for *all* transactions, even if no silent writes are executed in the common case. We hope that experience profiling applications will help us understand whether such heuristics are effective.

4.3.5 Discussion

While T-PASS divides the data into the aforementioned categories, it is important to remember to combine the information from all four reports when profiling and optimizing a transactional program.

For example, one way to reduce the synchronization overhead imposed by an atomic block is by privatizing some of the accessed data. In particular, if an atomic block processes a large data structure transactionally, where some portion of the structure is rarely accessed concurrently, then it often makes sense to use a short atomic block to make this portion inaccessible to other threads, then process it outside of an atomic block, and finally use another atomic block to make it publicly available again. Because the portion being privatized was rarely accessed concurrently, it is unlikely that making it inaccessible to other threads while processing it non-transactionally will cause other threads long delays due to waiting for the data to be publicly available again. To identify where this technique may be useful, we can use the T-PASS's basic characteristics report to identify atomic blocks whose execution time is dominated by long, large transactions. Then, to find out whether privatizing the data is likely to cause long waiting times for other threads, we can add gratuitous writes of that data, and check the conflicts analysis report to see if there are any conflicts with concurrent reads or writes. If conflicts involving the gratuitous write are sufficiently rare, privatizing the data is unlikely to delay other threads.

If an HTM mechanism is available, it can also help in reducing the synchronization overhead of atomic blocks by executing some of the user transactions using the hardware support. Profiling information can help by providing program-specific "hints" with regards to which transactions should be executed in hardware and which in software. What information is relevant for these hints depends on the limitation of the particular HTM mechanism. For example, with an HTM mechanism that can only execute transactions up to a certain size, we may want to detect transactions of a small data footprint, and see how much of the execution time was spent in them. If the HTM mechanism does not implement a good contention management policy, we may also want to check the contention overhead for these transactions, and so on.

Finally, we should remember to take all timing information with respect to the program execution time. A high value in the contention overhead report does not necessarily indicate a problem if the total time spent on these transactions is small compared to the total execution time. Knowing the sampling rate (that is, what fraction of the transactions are profiled), the profiler can easily project any timing information over all transactions, showing it as a fraction of the program execution time.

4.4 The T-PASS System Design

Figure 4.11 shows an overview of our profiling system. On the bottom, the user program calls the TM runtime to run transactions. The TM runtime is extended with a *runtime profiling support (RTPF)* extension that collects additional profiling information about transactions. The profiler runs in a separate process space. The RTPF extension reports to the profiler by calling *stubs*: empty reporting functions that do nothing except for isolating the profiled information as arguments. The profiler reads the reported information by tracing calls to these stubs and reading their arguments.

T-PASS uses DTrace [1] to trace the information reported via the stub calls. DTrace is a comprehensive dynamic tracing framework for the Solaris^{TM} operating system that supports tracing events in other processes with very low overhead. DTrace works well with multithreaded programs: for example, if two threads call the same stub concurrently, DTrace can detect and process these two

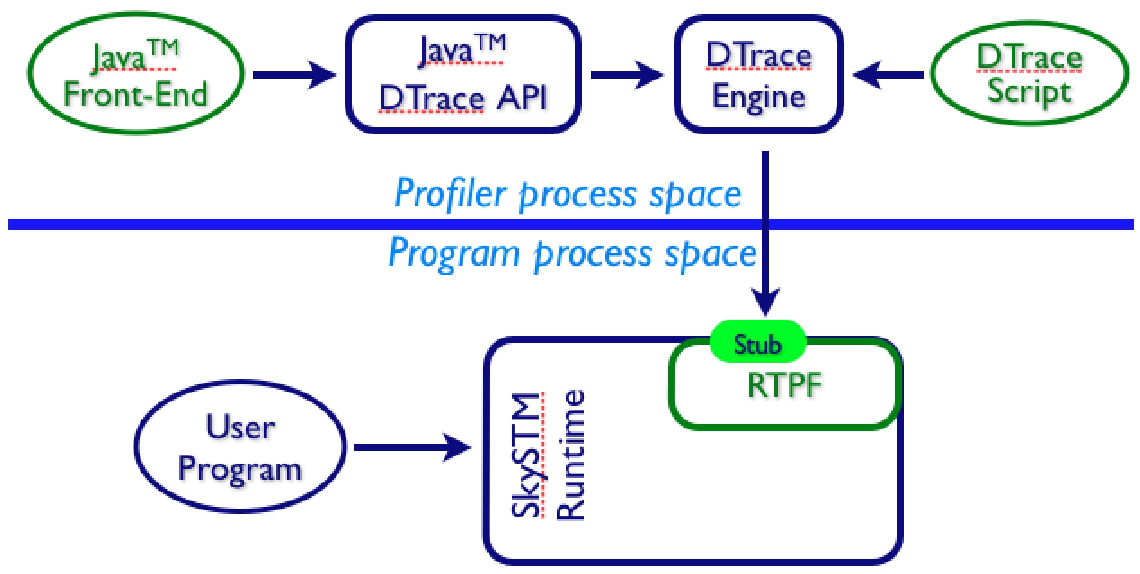


Figure 4.11: The T-PASS system design

calls concurrently without delaying all other threads. It also allows accessing the profiled program's memory space, for both reading and writing. The read access allows us to pass only key information by value to the stub, because DTrace can read any other information from the program's memory; the write access made the sampling mechanism more efficient, as we later describe.

The DTrace engine takes a DTrace script that describes which events need to be traced, and what actions should be executed when an event is traced. We used the DTrace Java API, which lets Java programs run DTrace scripts and capture their output, for aggregating and analyzing data. DTrace and its Java API provide low-overhead data collection combined with the flexibility of the Java Collections for data aggregation and filtering. For graphing support in Java we used the JFreeChart library [9].

The RTPF extension minimizes the number of stubs called by a single transaction, not only to minimize profiling overhead, but also to avoid skewing the transaction execution time that is reported to the profiler. Most profiling information is aggregated and reported when the profiled transaction terminates. In the cases in which we do report information during the transaction execution, we “fix” the transaction’s execution time by measuring and deducting the reporting time from it.

We implemented the RTPF extension for several configurations of the SkySTM [20] library: lazy or eager conflict detection, semi-visible or invisible reads, with or without implicit privatization support, plus a variety of contention management strategies. T-PASS allows us to compare the behavior of different runtime configurations on the same code.

4.4.1 Reducing Overhead

We keep the profiling costs under control by *sampling*: we collect information about only a small fraction of transactions. There are two sources of profiling costs: first there is the overhead introduced by the RTPF extension for collecting profiling data, and second there is the overhead caused by DTrace, when it stops threads that report data.

We addressed both by implementing the sampling mechanism in the RTPF extension, allowing the RTPF to collect data only for transactions that will be reported. The overhead for all other transactions consists only of querying whether the transaction is being profiled whenever profiling information may needed to be collected. While this may introduce minor imbalances because some transactions incur profiling overhead and some do not, we believe that random sampling ensures that any such perturbations will have only minor effects on observations.

Each thread performs its own sampling by maintaining a count-down counter, indicating how many physical transactions should be executed before one is profiled. Every (physical) transaction that is not profiled decrements the counter. Once the counter reaches zero, the thread profiles the next transaction, the data is reported by stub calls, and the counter is assigned a new random value. To get a uniform distribution with probability p, we assign the counter a random value from a geometric distribution with parameter p. Because each thread does its own sampling, it is possible to have different threads sample at different rates. We only experimented with the same sampling rate for all threads.

It is desirable to minimize profiling overhead while the profiler is not attached, so we can always compile programs with a TM runtime that supports profiling. To turn on profiling dynamically as needed, we take advantage of DTrace's ability to write the profiled program memory. The RTPF extension initializes the sampling rate for all threads to zero, so no transaction is profiled or reported. Every once in a while the RTPF calls a special profiling-enable-stub, providing DTrace with a pointer to a flag which it can set to request that profiling begin. This request can include parameters such as the requested sampling rate. The overhead when profiling is turned off is just the overhead for non profiled transactions, and the cost of periodically calling the profiling-enabled stub.

4.4.2 Extendability

For our prototype, we chose to use DTrace for communicating information between the profiled process and the profiler, because DTrace allowed us to quickly come up with a set of scripts to read and aggregate the profiled data, and to manipulate these scripts as we expanded and changed the profiled data while developing the profiler. Users of T-PASS can easily edit these scripts, or write their own, to examine different statistics on the profiled data, or to see more information about a particular data point. We note, however, that DTrace is not the only tool that can provide the data collection functionality; in particular, it can be replaced by *any* mechanism that can efficiently detect user function calls in a remote process. (For example, most debugger can provide this functionality, by placing breakpoints on the first statement in each stub function.) While using a different tool will require some changes in the profiler front-end (that is, the Java program that runs the DTrace scripts and aggregate the data), the RTPF layer can stay untouched.

Furthermore, T-PASS can be modified to work with a profiler front-end that runs as part of the profiled process. This can be done by replacing the stubs with non-empty functions that record and/or process the data. Having the RTPF layer report the information by passing it as parameters to the stubs gives us the flexibility of either reading the information remotely using DTrace (or a similar tool), or to record it locally by filling in the stubs with the appropriate recording functionality.

Finally, while T-PASS was designed to work with the SkySTM library, it can be extended to support additional TM runtimes without needing to change the profiler front-end, or the DTrace scripts that report the information to it. To support profiling for a TM runtime, the TM runtime designer will need to write a RTPF layer for that runtime so that it reports the profiled information using the stubs defined by the SkySTM RTPF layer. Furthermore, we believe that much of the code in the SkySTM RTPF layer could be used as-is when writing a RTPF layer for other TM runtimes.

4.5 Debugger Integration

In Chapter 3 we presented the `tm_db` [15] library that provides a range of transaction-related debugging features, effectively making the debugger transaction-aware. It is often useful to use such a transaction-aware debugger to see additional information for *some* of the profiled transactions. For example, Figure 4.4 shows that while most transactions were shorter than 15us, one transaction took longer than 100μs. One way to discover what happened is to rerun the program under a transaction-aware debugger, stopping when a transaction runs for longer than 100μs. This kind of scrutiny may reveal additional information not available to the profiler, such as the exact addresses that the transaction wrote (instead of *how many* unique locations it wrote). One advantage of DTrace is that it allows us to stop traced process at any point so the the user can attach a debugger. We can structure the DTrace script to stop the process if the information reported to the profiler satisfies certain conditions. These conditions can refer to any piece of profiled information, or even information gathered from multiple transactions. For example, it could stop when encountering the 10th transaction that executed for longer than 100μs with a write-set of fewer than 5 items.

Integration with a debugger encourages a two-phase profiling methodology. First, run the program in the profiler, to accumulate broad-ranging statistics. After identifying phenomena of interest, run the program again, using the first-run statistics to instruct DTrace to halt the program when something interesting occurs.

4.5.1 Replay Debugging

As described in Chapter 2, to replay a transaction's execution in a debugger it is enough to know the *pre-transaction values* of all locations the transaction read. Given the pre-transaction values the debugger can reconstruct the value returned by each of the transaction's reads by re-executing the transaction, and logging writes in a new, initially empty write set. Each read returns the pre-transaction value, unless that location is in the write set, in which case it returns the write-set value. Knowing the value returned by all of the transaction's reads, the debugger can accurately replay the transaction's execution, assuming that the code is deterministic in the read values: that is, it behaves the same given the same read values.

While providing the pre-transactional values for *all* transactions may be costly, we can still support replay for only *profiled* transactions. Because we profile only a small sample of the transactions, and because we need to keep track of additional information for these transactions anyway, it is possible to keep the information required for replaying with a reasonable cost.

Here is how we do it. Instead of keeping track of pre-transaction values for locations read, we simply log all values returned by transactional reads, in execution order. Hence, there is no need to maintain a write set during replay, because the read values are known without checking whether the location was written. Indeed, we do not even need to log read addresses, only the value returned by each read in sequence. We can even replay aborted transactions, which, in some TM run-times, may have seen an inconsistent state.

Here is a new and simple way to support transaction replay by exploiting the TM run-time's ability to retry failed transactions. When we decide to replay a transaction, we deceive the run-time into thinking that the commit failed, and the run-time then reschedules that transaction. The second time around, however, the transaction runs in a special side-effect free replay mode, where reads return the logged values, and writes are suppressed.

In more detail, at run-time a transaction is in either a *regular* or a *replay* mode (the default is regular). To replay a transaction, DTrace stops the transaction just before it tries to commit, and sets a flag requesting a replay. This can be easily done because the RTPF extension calls the stub to report the profiled information at commit time, allowing DTrace to respond by setting the flag if the transaction should be replayed. After attaching the debugger, the commit proceeds as usual except that when it is done, it caches the outcome (success or failure), changes the transaction mode to replay and regardless of the actual outcome, reports that the transaction commit failed, tricking the run-time into retrying the transaction. The second time around, when the transaction commits in replay mode, it simply resets the transaction mode to regular, and returns the cached result of the first commit attempt. In replay mode, a transactional read simply returns the value logged for that read, and a transactional write does nothing. Finally, if a replaying transaction does a read validation, that validation succeeds unless the original transaction failed *and* there are no more logged read values to return.

We implemented the replay mechanism in the RTPF extension of SkySTM, together with structuring the DTrace script to stop and replay transactions whose execution time is longer than a given value. We then examined the long transactions in the hash table execution shown in Figure 4.4. It turns out that the long transactions were the ones that resized the hash table.

Further examination yielded an interesting observation, explaining why we rarely see very high contention overhead even for transactions that have only two trials (Figure 4.6). If two transactions try to add a value to a hash table that has to be resized, they will conflict (even if the values are added in different buckets). One transaction will successfully resize the table, and the other will be retried. The second trial will not need to resize, and will be much shorter, resulting in a high ratio between the overall and the useful transaction time. Using the combination of a profiler and a debugger, we observe that sometimes high contention overhead is reported because different trials do different things, when the underlying data structure has changed between the trials.

Note that in principle, the technique introduced here where a transaction pretends to abort to trick the run-time into replaying, can be used with any debugger, not just a transaction-aware debugger using `tm_db`. Of course, a transaction-aware debugger will report more meaningful information.

4.6 Discussion

We presented T-PASS, a prototype system for profiling transactional programs. T-PASS provides profiling information in various categories, as well as a flexible querying mechanism, to address bottlenecks that are commonly found in transactional programs.

We believe T-PASS shows that TM can make concurrent programs easier to profile. Although a lock-based system could instrument locks and critical sections, the principal difference between locking and TM is that TM run-times naturally keep track of much more information about data accesses, so it becomes possible to track data accesses at a finer level of granularity.

In addition, the speculative nature of many TM run-time systems is helpful for choosing an appropriate synchronization granularity. Locks ensure that conflicting critical sections do not run concurrently. Because locking must be conservative, it may not be possible to detect when critical sections are too coarse-grained. Because TM run-times detect conflicts dynamically, the profiler can aggregate and format fine-grained information about actual conflicts to allow programmers to detect when a program's performance might be improved by refactoring the atomic block granularity.

TM runtimes and transactional programming are still in their infancy, and therefore the kind of bottlenecks that a profiler needs to look for are likely to change over time. For example, the recently proposed NOrec TM runtime [4] does not map the user-level data to metadata; instead, it uses a global lock to serialize all writing transactions, and a value based validation scheme to guarantee that a transaction reads consistent data. Thus, the NOrec TM runtime eliminates the false conflicts problem, which may significantly affect the way profiling data should be presented to the user.

Another example is that of TM runtimes that may support true closed nesting of transactions. Our profiler assumes only the simplest form of nesting, called *flattening*, where a nested atomic block is executed as part of the parent transaction that executes the outermost atomic block. Thus, with flattening, losing a conflict with an access in a nested atomic block causes the whole outermost atomic block to be retried. With true closed nesting, on the other hand, a conflict with an access inside a nested atomic block may cause only the execution of that atomic block to be retried, which may significantly change the kind of cost analysis that T-PASS needs to present the user with in the present of conflicts (e.g. the cost of losing a conflict changes, etc.).

Finally, emerging HTM mechanisms may introduce different limitations on transactions, requiring profilers to appropriately adapt.

Chapter 5

Conclusions

In this dissertation we investigated the debugging and profiling needs of transactional programs. We showed why debuggers will have to change to support even just the most basic debugging features for transactional programs, and demonstrated the additional power that TM provides to support more advanced debugging capabilities. We showed how to build an infrastructure to support debugging of transactional programs with various STM runtimes, and built a library to provide such an infrastructure. To better understand the performance characteristics of transactional programs, we built a profiling prototype that identifies performance bottlenecks in the program, and provides guidance for how to optimize it in both software and hybrid TM environments.

To date, there are very few realistic parallel programs that use transactional memory, and most of those that do were converted from lock-based programs by replacing critical sections with atomic blocks. In many cases, this method resulted in transactional programs that did not scale due to unnecessary sharing of data between atomic blocks [5], or in programs that did scale but performed badly comparing to the original lock-based program due to the high overhead of the STM runtime [18, 2]. While preliminary experience with writing transactional programs "from scratch" indicates that it can significantly simplify concurrent programming [29], it is clear that there is still a long way to go before we understand how transactional programs should be designed to make writing efficient concurrent programs easier.

We believe that our work on debugging and profiling of transactional programs is a necessary key step towards building this understanding. The infrastructure and tools that we built significantly simplify the task of writing transactional programs and understanding their needs. In the future, we plan to use these tools to explore how realistic parallel programs can be better designed to use transactional memory, and other newly available synchronization mechanisms. We expect that this research direction will provide guidance not only for writing better parallel programs, but also for improving TM runtimes, the hardware support that they require, and the interface to the programmer, resulting in a better environment for writing parallel programs.

One interesting direction to explore is whether and how the integration of TM with programming languages should change to allow addressing bottlenecks presented by the profiler. Here are a few examples:

- Write upgrades and silent writes: can the programmer mark particular read statements that are likely to be upgraded, or particular write statements that are likely to be silent, and have the compiler generate the required code to avoid the unnecessary overhead in these special cases?

- Contention management: can the programmer annotate particular atomic blocks, or even particular accesses, to affect the contention management policy applied to these statements (e.g. by applying different priorities to atomic blocks)?

- False conflicts: can the programmer ask the TM runtime that two particular accesses will not falsely conflict (for example by annotating them with different IDs, and having the TM runtime re-assign orecs in case that two accesses to different variables with different IDs map to the same orec)? While avoiding *all* false conflicts may be costly, doing so for only a few accesses that are usually conflicting may be worthwhile.

While these examples may be helpful for improving performance of transactional programs, they also complicate the interface to the programmer and are better avoided. Therefore, another interesting direction to explore is whether the profiler can directly feed the compiler with profiling information, and have the compiler generate the appropriate optimized code without having users manually annotate their code. For example, the compiler can implant requests to write access a variable before it is first read if the profiler indicates that this read statement is usually upgraded. In some cases this process can be only partly automated, where the user is asked for their preferences in cases where it is not clear what optimization to apply based only on the profiled data.

Finally, another important future research direction is that of debugging and profiling support for HTM mechanisms. To date, most HTM proposals do not provide any debugging capabilities for transactions that they run. In this dissertation we described how in a hybrid environment the debugger can force a user transaction to be run using STM, so that it can be debugged, but we did not discuss debugging mechanisms for transactions that are run using the HTM. Lev and Maessen [22] proposed the `SpHT` mechanism, which augments a best-effort HTM with a software component to improve the debugging capabilities of user transactions, while still taking advantage of the HTM when running them. The `SpHT` mechanism can run transactions significantly faster than an equivalent software only solution, but still imposes a significant overhead due to logging of the transaction's reads and writes, which is done in software. We hope that future work on HTM design will improve the debugging capabilities of newly available HTM mechanisms; we believe that our work, which defined an interface for transactional debugging support, is a first step towards achieving this goal.

5.1 Open Source

Most of the work described in this dissertation is made open source and will be soon available to the public at `http://www.cs.brown.edu/people/levyossi/Thesis/`.

In particular, the extended version of the SkySTM library with the runtime debugging and profiling support (the RTDB and RTPF layers), as well as the SkySTM's RDM modules, will be available as open source. We hope that the availability of the RDM and the RTDB code will encourage other researchers to extend additional TM runtimes with transactional debugging support, by writing new RDM components that will be used with the tm_db library and the transactional debugging extension of the Sun Studio dbx debugger that uses it.

In addition, we are making the code of the tm_db library itself available, to help researchers who may want to adapt it to other debuggers as well, or experiment with additional debugging features.

Finally, because the T-PASS Java front-end is still in an initial development stage, we are not yet open sourcing it; instead, we are providing a variety of DTrace scripts that demonstrate how the profiling information collected by the RTPF layer can be extracted and presented to the user.

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