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LOWER BOUNDS AND IMPOSSIBILITY RESULTS FOR TRANSACTIONAL MEMORY COMPUTING

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Abstract

We overview some impossibility results and lower bounds on the complexity of implementing software transactional memory, and explain their underlying assumptions.

1 Introduction

As anyone with a laptop or an Internet connection knows, the multi-core revolution is here, since almost any computing appliance contains several processing cores. With the improved hardware comes the need to harness the power of concurrency, since the processing power of individual cores does not increase. Applications must be restructured in order to reap the benefits of multiple processing units, without paying a hefty price for coordination among them.

It has been argued that writing concurrent applications is significantly more challenging than writing sequential ones, and Transactional memory (TM) has been suggested as a way to deal with this difficulty. In the simplest form of TM, the programmer need only wrap code with operations denoting the beginning and end of a transaction. The transactional memory will take care of synchronizing the shared memory accesses so that each transaction seems to execute sequentially and in isolation.

Originally suggested as a hardware platform by Herlihy and Moss [29], TM has resurfaced as a software mechanism a couple of years later. The first software implementation of transactional memory was suggested by Shavit and Touitou [43]: it provided, in essence, support for multi-word synchronization operations on a static set of data items, in terms of a unary operation (LL/SC), somewhat optimized over prior implementations, e.g., [9, 46]. Shavit and Touitou
coined the term *software transactional memory* (STM) to describe their implementation.

Only when the termination condition was relaxed to *obstruction freedom* (see Section 2.2), the first STM handling a dynamic set of data items was presented by Herlihy et al. [28]. Work by Rajwar et al., e.g., [38, 41], helped to popularize the TM approach in the programming languages and hardware communities.

Despite its simplicity, or perhaps because of it, transactional memory implementations incur significant cost, as has been discovered in recent theoretical work. This short survey describes several of these impossibility results and lower bounds, and their interaction with various properties of transactional memory.

## 2 Formalizing TM

This section outlines how transactional memory can be formally captured, as well as properties expected of it. A comprehensive in-depth treatment is provided by Guerraoui and Kapalka [25].

The model encompasses at least two levels of abstraction: The high level has transactions, each of which is a sequence of operations accessing data items. At the low level, the operations are translated into executions in which a sequence of events apply *primitive operations* (or *primitives*) to base objects, containing the data and the meta-data needed for the implementation. (See Figure 1.)

A transaction is a sequence of operations executed by a single process on a set of data items, shared with other transactions. Data items are accessed by *read* and *write* operations; some systems also support other operations. The interface also includes *try-commit* (*tryC*) and *try-abort* (*tryA*) operations, in which a transaction requests to commit or abort, respectively. If the response of *try-commit* is *commit*, the writes of the transaction are ensured to take effect, and we say that the transaction is committed. Any of these operations, not just *try-abort*, may cause the transaction to abort, in which case, none of its writes take effect and we say that the transaction is aborted. If the transaction is aborted not in response to *try-abort*, we say that it is forcibly aborted.

The collection of data items accessed by a transaction is its *data set*; the items written by the transaction are its *write set*, with the other items being its *read set*.

![Figure 1: Levels of abstraction in transactional memory.](image-url)
A software implementation of transactional memory (abbreviated STM) provides data representation for transactions and data items using base objects, and algorithms, specified as primitives on the base objects. These procedures are followed by asynchronous processes in order to execute the operations of transactions. The primitives can be simple reads and writes, but also more sophisticated ones, like cas or dcas, typically applied to memory locations, which are the base objects for the implementation.

When processes invoke these procedures, in an interleaved manner, we obtain executions, in the standard sense of asynchronous distributed computing (cf. [8]). Executions consist of configurations, describing a complete state of the system at some point in time, and events, describing a single step by an individual process, including an application of a single primitive to base objects (possibly several objects, e.g., in case of dcas).

The interval of a transaction T is the execution interval that starts at the first event of T and ends at the last event of T. If T does not have a last event in the execution, then the interval of T is the (possibly infinite) execution interval starting at the first event of T. Two transactions overlap if their intervals overlap.

2.1 Safety: Consistency Properties of TM

An STM is serializable if committed transactions appear to execute sequentially, one after the other [39]. An STM is strictly serializable if this serialization order preserves the order of non-overlapping transactions [39]. This notion is called order-preserving serializability in [47], and is the analogue of linearizability [31] for transactions.

Opacity, suggested by Guerraoui and Kapalga [23], further demands that even partially executed transactions, which may later abort, must be serializable (in an order-preserving manner). Opacity also accommodates operations beyond read and write.

While opacity is a stronger condition than serializability, snapshot isolation [10] is a consistency condition weaker than serializability. Roughly stated, snapshot isolation ensures that all read operations in a transaction return the most recent value as of the time the transaction starts; the write sets of concurrent transactions must be disjoint. (Cf. [47, Definition 10.3].) Riegel et al. [42] proposed to use snapshot isolation for TM.

Virtual World Consistency (VWC), defined by Imbs et al. [32], is a weakening of opacity, tailored for transactional memory. VWC allows aborted (and ongoing)
transactions to observe *mutually inconsistent* views of the execution, as long as each of them is consistent with some sequential execution of the committed transactions in their “causal past”. A related condition, called *Transactional Memory Specification* (referred to as TMS1), was suggested by Doherty et al. [16], also considers each aborted transaction in isolation.

Figure 2 summarizes these conditions and the relations between them. Additional discussion of the relations between various TM and database consistency conditions is given by Attiya and Hans [26].

### 2.2 Progress: Termination Guarantees for TM

One of the innovations of TM is in allowing transactions not to commit, when they are faced with conflicting transactions, namely, transactions that access the same data items. This, however, admits trivial implementations where no progress is ever made. Finding the right balance between nontriviality and efficiency has lead to several progress properties. They are first and foremost distinguished by whether locking is accommodated or not.

When locks are not allowed, the strongest requirement—rarely provided—is of *wait-freedom*, namely, that each transaction has to eventually commit. A weaker property ensures that some transaction eventually commits, or that a transaction commits solo, for long enough time. The last property is called *obstruction-freedom* [28] (see further discussion in [4]).

A *lock-based STM* (e.g., TL2 [15]) is often required to be *(weakly) progressive* [24], namely, a transaction that does not encounter a conflicting transaction
must commit. (There is a conflict between two transactions, if both of them access the same data item.)

Several lower bounds assume a minimal progress property, ensuring that a transaction terminates successfully if it runs alone, from a situation in which no other transaction is pending. This property is implied both by obstruction freedom and by weak progressiveness.

Related definitions [18, 24, 34] further attempt to capture the distinction between aborts that are necessary in order to maintain the safety properties (e.g., opacity) and spurious aborts that are not mandated by the consistency property, and to measure their ratio.

Strong progressiveness [24] ensures that even when there are conflicts, some transaction commits. More specifically, an STM is strongly progressive if a transaction without nontrivial conflicts, namely, a conflict involving at least one write, is not forcibly aborted, and if a set of transactions have nontrivial conflicts on a single item then not all of them are forcibly aborted. (Recall that a transaction is forcibly aborted, when the abort was not requested by a try-abort operation of the transaction, i.e., the abort is in response to try-commit, read or write operations.)

Permissiveness tries to capture the number of unjustified, spurious aborts; it requires a transaction to commit unless doing so violates correctness [20]; said otherwise, this means that a transaction can abort or block only if committing may violate correctness. A weaker condition, given by Fan et al. [40], says that an STM is multi-version (MV)-permissive if a transaction is forcibly aborted (not because it requests to abort) only if it is an update transaction that has a nontrivial conflict with another update transaction.

Strong progressiveness and MV-permissiveness are incomparable: The former allows a read-only transaction to abort, if it has a conflict with another update transaction, while the latter does not guarantee that at least one transaction is not forcibly aborted in case of a conflict.

Figure 3 shows the relations between these progress conditions.

**Remark 1.** Strictly speaking, these properties are not liveness properties in the traditional sense [36], since they can be checked in finite executions.

### 2.3 Performance Indicators

There has been some theoretical attempts to predict how well will TM implementations scale, resulting in definitions that postulate behaviors that are expected to yield superior performance.
2.3.1 Disjoint-Access Parallelism

The most accepted such notion is disjoint-access parallelism, capturing the requirement that unrelated transactions progress independently, even if they occur at the same time. That is, an implementation should not cause two transactions, which are unrelated at the high-level, to simultaneously access the same low-level shared memory.

We explain what it means for two transactions to be unrelated through a conflict graph that represents the relations between transactions. The conflict graph of an execution interval $I$ is an undirected graph, where vertices represent transactions whose execution intervals intersect, and edges connect transactions that share a data item. Two transactions $T_1$ and $T_2$ are disjoint access if there is no path between the vertices representing them in the conflict graph of their execution intervals; they are strictly disjoint access if there is no edge between these vertices.

Below is the conflict graph for six transactions: $T_1$ with data set \{A, B, C\}, $T_2$ with data set \{A, D\}, $T_3$ with data set \{D, E\}, $T_4$ with data set \{F, L\}, $T_5$ with data set \{L\} and $T_6$ with data set \{J\}.

In this example, the data sets of $T_1$ and $T_2$ intersect, as do the data sets of $T_2$ and $T_3$, while the data sets of $T_1$ and $T_3$ do not intersect. Hence, $T_1$ and $T_3$ are strictly disjoint access, but they are not disjoint access.
Two events *contend* on a base object $o$ if they both access $o$, and at least one of them applies a nontrivial primitive to $o$. (A primitive is *nontrivial* if it may change the value of the object, e.g., a write or cas; otherwise, it is *trivial*, e.g., a read.) Transactions *concurrently contend* on a base object $o$ if they have pending events at the same configuration that contend on $o$.

**Property 1** (Disjoint access parallelism (weak)). An STM implementation is (weakly) disjoint-access parallel if two transactions concurrently contend on the same base object only if they are not disjoint access.

This definition captures the first condition of the disjoint-access parallelism property of Israeli and Rappoport [33], in accordance with most of the literature (cf. [30]). It is somewhat weaker, as it allows two processes to apply a trivial primitive on the same base object, e.g., read, even when executing disjoint-access transactions. Moreover, this definition only prohibits concurrent contending accesses, allowing transactions to contend on a base object $o$ at different points of the execution. A stronger requirement is:

**Property 2** (Disjoint access parallelism (strong)). An STM implementation is disjoint-access parallel if two transactions concurrently access the same base object only if they are not disjoint access.

The original disjoint-access parallelism definition [33] also restricts the impact of concurrent transactions on the *step complexity* of a transaction.

For additional definitions and discussion, see [6].

### 2.3.2 Invisibility of Reads

It is expected that many typical applications will generate workloads that include a significant portion of *read-only* transactions. This includes, for example, transactions to search a data structure, and find whether it contains a particular data item.

Many STMs attempt to optimize read-only transactions, and more generally, the implementation of read operations inside the transaction. By their very nature, read operations, and even more so, read-only transactions, need not leave a mark on the shared memory, and therefore, it is desirable to avoid writing in such transactions, i.e., to make sure that reads are *invisible*, and certainly, that read-only transactions do not write at all.

**Remark 2.** Dice et al. [14] refer to a transaction as having invisible reads even if it writes, but the information is not sufficiently detailed to supply the exact details about the transaction’s data set. (In their words, “the STM does not know which, or even how many, readers are accessing a given memory location.”) This behavior is captured by the stronger notion of an oblivious STM [5].
2.3.3 Makespan Ratio

Some transactional memories come with a scheduler, determining which transaction to abort when there is a danger of violating consistency. One way to evaluate a transactional scheduler, borrowed from scheduling theory, is to measure its makespan, namely, the total time it takes to complete all the transactions in a specific workload.

Reducing the makespan is a major challenge, since transactions are often aborted and restarted. Measuring the makespan of a workload by itself is not indicative for the performance of a transactional scheduler, since the workload might be inherently sequential. Instead, the performance of a transactional scheduler is evaluated by the ratio, over all possible workloads, between its makespan and the makespan of an optimal, clairvoyant scheduler that knows the list of resource accesses that will be performed by each transaction, as well as its release time and duration \[3, 21\]. This idealistic transactional scheduler captures the inherent makespan needed to perform the workload, under complete knowledge, and the ratio captures the cost of the lack of this knowledge.

3 TM Lower Bounds and Impossibility Results

This section overviews research on the inherent complexity of TM. This includes several impossibility results showing that certain properties simply cannot be achieved by a TM, and a few worst-case lower bounds showing that other properties put a high price on the TM, often in terms of the number of steps that should be performed, or as bounds on the local computation involved.

3.1 Inherent Cost of TM Implementations

An early result demonstrates the additional cost of opacity over serializability, namely, the cost of making sure that the values read by a transaction are consistent as it is in progress (and not just at commit time, as done in many database implementations). Guerraoui and Kapalka \[23\] showed that the number of steps in a read operation is linear in the size of the invoking transaction’s read set, assuming that reads are invisible, the STM keeps only a single version of each data item, and is progressive (i.e., it never aborts a transaction unless it conflicts with another pending transaction). In contrast, when only serializability has to be guaranteed, the values read can be validated only at commit time, leading to significant savings.

Another way to study the complexity of TM implementations is to prove lower bounds on objects that can be derived from them, for example, atomic snapshot
objects [1]. Attiya et al. [2] have shown that if a wait-free implementation of an \( m \)-component snapshot object from historyless objects is space optimal, then its step complexity is in \( \Omega(m) \). This follows from lower bounds for a new, more general class of implementations from base objects of any type.

Not all kinds of steps are created equal, and some steps involve more expensive synchronization than others, for example, those that force a memory barrier to occur. Kuznetsov and Ravi [35] have shown that if an STM implementation ensures a high degree of concurrency, i.e., it is permissive, then the number of expensive synchronization steps performed by a transaction is linear in its read-set size. The paper also demonstrates that only a constant number of synchronization steps is needed in each transaction of a strongly progressive STM; note that such STMs provide limited degree of concurrency. Nevertheless, even in strongly progressive STMs, a transaction must protect (e.g., by using locks or strong synchronization primitives) an amount of data that is linear in its write-set size.

### 3.2 The Consensus Number of TM

Consensus is a core problem in distributed computing, requiring processes to agree on one of their inputs. The consensus number of a data structure [27] is the maximal number of processes that can solve consensus using copies of the data structure (and read/write registers); the universality of consensus means that an object with consensus number \( c \) can wait-free implement every other data structure, for \( c \) processes, and that there are problems (specifically, consensus) that have no wait-free solution from the data structure (and read / write registers), for more than \( c \) processes.

Guerraoui and Kapalka [22] have shown that lock-based and obstruction-free TMs can solve consensus for at most two processes, that is, their consensus number is 2. An intermediate step shows that such TMs are equivalent to shared objects that fail in a very clean manner [4]. Roughly speaking, this is a consensus object providing a familiar propose operation, allowing a thread to provide an input and wait for a unanimous decision value; however, the propose operation may return a definite fail indication, which ensures that the proposed value will not be decided upon. Intuitively, an aborted transaction corresponds to a propose operation returning false. To get the full result, further mechanisms are needed to handle the long-lived nature of transactional memory.

### 3.3 Providing Disjoint-Access Parallelism

Guerraoui and Kapalka [22] prove that obstruction-free implementations of software transactional memory cannot ensure strict disjoint-access parallelism. This property requires transactions with disjoint data sets (with strict disjoint access)
Table 1: Impossibility of achieving disjoint access parallelism (DAP). The table entry shows the progress condition needed for proving the result.

not to access a common base object. This notion is stronger than disjoint-access parallelism (Property 1), which allows two transactions with disjoint data sets to access the same base objects, provided they are connected via other transactions. Note that the lower bound does not hold under this more standard notion, as Herlihy et al. [28] present an obstruction-free and disjoint-access parallel STM.

The result that obstruction-free implementations of software transactional memory cannot ensure strict disjoint-access parallelism, has been extended in several important ways.

For the stronger case of wait-free read-only transactions, the assumption of strict disjoint-access parallel can be replaced with the assumption that read-only transactions are invisible. Specifically, an STM cannot be disjoint-access parallel and have invisible read-only transactions that always terminate successfully [6]. A read-only transaction not only has to write, but the number of writes is linear in the size of its read set. Both results hold for strict serializability, and hence also for opacity. With a slight modification of the notion of disjoint-access parallelism, i.e., strong disjoint-access parallelism (Property 2), these results also hold for serializability and snapshot isolation.

In fact, even the original result of Guerraoui and Kapalka [22] holds with snapshot isolation: Bushkov et al. [11] have shown that it is impossible to ensure strict disjoint-access parallelism and obstruction-freedom even if we weaken safety to ensure only snapshot isolation.

Another extension, by Ellen et al. [17], shows that transactional memory implementations cannot ensure both disjoint-access parallelism and wait-freedom; this assumes that the TM requires a process to re-execute its transaction if it has been aborted and that the TM guarantees that each transaction is aborted only a limited number of times.

Table 1 summarizes these impossibility results.
3.4 Privatization

An important goal for STM is to access certain items by simple reads and writes, without paying the overhead of the transactional memory. It has been shown [19] that, in many cases, this cannot be achieved without prior privatization [44, 45], namely, invoking a privatization transaction, or some other kind of a privatizing barrier [14].

Attiya and Hillel [5] have proved that, unless parallelism (in terms of progressiveness) is greatly compromised or detailed information about non-conflicting transactions is tracked (the STM is not oblivious), ensuring that no transaction writes to privatized data, incurs a cost (in terms of memory location accessed), which is linear in the number of items that are privatized.

3.5 Avoiding Aborts

An early result by Guerraoui et al. [20] shows that ensuring opacity, together with permissiveness is NP-hard. Similarly, Keidar and Perelman [34] prove that an opaque, strongly progressive STM requires NP-complete local computation, while a weaker, online notion requires visible reads.

The competitive ratio of the makespan is another way to measure the number of unnecessary aborts. It has been shown that the best competitive ratio achieved by simple transactional schedulers is $\Theta(s)$, where $s$ is the number of data items [3].

Attiya and Milani [7] studied the makespan of transactional scheduling under read-dominated workloads. These common workloads include read-only transactions, i.e., those that only observe data, and late-write transactions, i.e., those that update only towards the end of the transaction. This work shows that while read-only transactions are easily handled to achieve good makespan, late-write transactions significantly deteriorate the competitive ratio of any non-clairvoyant scheduler, assuming it takes a conservative approach to conflicts.

3.6 Limiting Progress

Local progress is a liveness property, which states that every process which is not parasitic (i.e., does not keep executing transactional operations without ever attempting to commit) and does not crash, makes progress. Bushkov et al. [12] defined this notion and proved that no TM implementation can ensure both opacity and local progress; in fact, the result holds also under the assumption of strict serializability.

Moreover, Crain et al. [13] have proved that opacity is incompatible even with probabilistic permissiveness, assuming reads are invisible. This means that there
is no probabilistically permissive STM system that implements opacity while ensuring read invisibility. In contrast, probabilistic permissiveness can be obtained with the weaker condition, VWC [13].

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