Software Transactional Memory with Interactions
Extended Version

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Abstract Software Transactional memory (STM) is an emerging abstraction for concurrent programming alternative to lock-based synchronizations. Most STM models admit only isolated transactions, which are not adequate in multithreaded programming where transactions need to interact via shared data before committing. To overcome this limitation, in this paper we present Open Transactional Memory (OTM), a programming abstraction supporting safe, data-driven interactions between composable memory transactions. This is achieved by relaxing isolation between transactions, still ensuring atomicity. This model allows for loosely-coupled interactions since transaction merging is driven only by accesses to shared data, with no need to specify participants beforehand.

1 Introduction

Modern multicore architectures have emphasized the importance of abstractions supporting correct and scalable multi-threaded programming. In this model, threads can collaborate by interacting on shared data structures, such as tables, message queues, buffers, etc., whose access must be regulated to avoid inconsistencies. Traditional lock-based mechanisms (like semaphores and monitors) are notoriously difficult and error-prone, as they easily lead to deadlocks, race conditions and priority inversions; moreover, they are not composable and hinder parallelism, thus reducing efficiency and scalability. Transactional memory (TM) has emerged as a promising abstraction to replace locks \cite{5,20}. The basic idea is to mark blocks of code as atomic; then, execution of each block will appear either as if it was executed sequentially and instantaneously at some unique point in time, or, if aborted, as if it did not execute at all. This is obtained by means of optimistic executions: these blocks are allowed to run concurrently, and eventually if an interference is detected a block is automatically restarted after that its effects are rolled back. Thus, each transaction can be viewed in isolation as a single-threaded computation, significantly reducing the programmer’s burden.

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Moreover, transactions are composable and ensure absence of deadlocks and priority inversions, automatic roll-back on exceptions, and increased concurrency.

However, in multi-threaded programming transactions may need to interact and exchange data before committing. In this situation, transaction isolation is a severe shortcoming. A simple example is a request-response interaction between two transactions via a shared buffer. We could try to synchronize the threads accessing the buffer $b$ by means of two semaphores $c_1$, $c_2$ as follows:

```
// Party1 (Master)         // Party2 (Worker)
atomically {
  up(c1);                atomically {
  <put request in b>     down(c1); // wait for data
  <some other code; may abort>     <get request from b>
  down(c2); // wait for answer     <compute answer; may abort>
  <get answer from b; may abort>     <put answer in b>
}
```

Unfortunately, this solution does not work: any admissible execution requires an interleaved scheduling between the two transactions, thus violating isolation; hence, the transactions deadlock as none of them can progress. It is important to notice that this deadlock arises because interaction occurs between threads of different transactions; in fact, the solution above is perfectly fine for threads outside transactions or within the same transaction.

To overcome this limitation, in this paper we propose a programming model for safe, data-driven interactions between memory transactions. The key observation is that atomicity and isolation are two disjoint computational aspects:

- an atomic non-isolated block is executed “all-or-nothing”, but its execution can overlap others’ and uncontrolled access to shared data is allowed;
- a non-atomic isolated block is executed “as if it were the only one” (i.e., in mutual exclusion with others), but no rollback on errors is provided.

Thus, a “normal” block of code is neither atomic nor isolated; a mutex block (like Java synchronized methods) is isolated but not atomic; and a usual STM transaction is a block which is both atomic and isolated. Our claim is that atomic non-isolated blocks can be fruitfully used for implementing safe composable interacting memory transactions—henceforth called open transactions.

In this model, a transaction is composed by several threads, called participants, which can cooperate on shared data. A transaction commits when all its participants commit, and aborts if any thread aborts. Threads participating to different transactions can access to shared data, but when this happens the transactions are transparently merged into a single one. For instance, the two transactions of the synchronization example above would automatically merge becoming the same transaction, so that the two threads can synchronize and proceed. Thus, this model relaxes the isolation requirement still guaranteeing atomicity and consistency; moreover, it allows for loosely-coupled interactions since transaction merging is driven only by run-time accesses to shared data, without any explicit coordination among the participants beforehand.
Related work. Many authors have proposed mechanisms to allow transactions to interact. Perhaps the work closest to ours are transaction communicators (TC) [9]. A transaction communicator is a (Java) object which can be accessed simultaneously by many transactions. To guarantee consistency, dependencies between transactions are maintained at runtime: a transaction can commit only when every transactions it depends on also commit. When dependencies form a cycle, the involved transactions must either all commit or abort together. This differs from OTM approach, where cooperating transactions are dynamically merged and hence the dependency graph is always acyclic; thus, OTM is opaque whereas TC is not. Other differences between TC and OTM are that our model has a formal semantics and that it can be implemented without changing neither the compiler nor the runtime (albeit it may be not very efficient).

Other authors have proposed events- and message passing-based mechanisms; we mention transactional events (TE) [1], which are specialized to the composition of send/receive operations to simplify synchronization in communication protocols, and TIC [21], where a transaction can be split into an isolated and a non-isolated transactions; this may violate local invariants and hence TIC does not satisfy opacity. Finally, communicating memory transactions (CMT) [8] is a model combining memory transactions with the actor model yielding transactors; hence CMT can be seen as the message-oriented counterpart of TC. CMT is opaque and has an efficient implementation; however it is best suited to distributed scenarios, whereas TC and OTM are aimed to multi-threaded programming on shared memory—in fact, transactors can be easily implemented in OTM by means of queues on shared memory. Another difference is that channel topology among transactors is established a priori, i.e. when the threads are created, while in OTM threads are created at runtime and interactions between transactions are driven by access to shared data only, whose references can be acquired at runtime.

Despite the name, our open transactions do not have much to share with open nested transactions [15]. The latter work is about enabling physically conflicting executions of transactions, still maintaining isolation from the programmer’s point of view; hence, open nested transactions cannot actually interact.

Synopsis. In Section 3 we present Open Transactional Memory in the context of Concurrent Haskell. In Section 5 we provide a formal operational semantics which is used in Section 6 to prove that OTM satisfies the opacity correctness criterion. Concluding remarks and directions for future work are in Section 7.

2 Background: Concurrency Control in Haskell

In this paper we focus on internal concurrency, i.e. multiple threads in a single process cooperating through shared memory. The dominant technique is lock-based programming which can quickly become unmanageable as interactions grow in complexity. In the last decade, transactional memory has seen increasing adoption as an alternative to locks.

In this section we briefly recall these approaches in the context of Haskell.
2.1 Concurrent Haskell

Haskell was born as pure lazy functional language; side effects are handled by means of monads [18]. For instance, I/O actions have type \( \text{IO} \ a \) and can be combined together by the monadic bind combinator \( >>= \). Therefore, the function \( \text{putChar} :: \text{Char} \to \text{IO} \ () \) takes a character and delivers an I/O action that, when performed (even multiple times), prints the given character. Besides external inputs/outputs, values of \( \text{IO} \) include operations with side effects on mutable (typed) cells. A cell holding values of type \( a \) has type \( \text{IORef} \ a \) and may be dealt with only via the following operations:

\[
\begin{align*}
\text{newIORef} &:: a \to \text{IO} \ (\text{IORef} \ a) \\
\text{readIORef} &:: \text{IORef} \ a \to \text{IO} \ a \\
\text{writeIORef} &:: \text{IORef} \ a \to a \to \text{IO} \ ()
\end{align*}
\]

Concurrent Haskell [19] adds support to threads which independently perform a given I/O action as explained by the type of the thread creation function:

\( \text{forkIO} :: \text{IO} () \to \text{IO} \ \text{ThreadId} \)

The main mechanism for safe thread communication and synchronisation are \( \text{MVars} \). A value of type \( \text{MVar} \ a \) is mutable location (as for \( \text{IORef} \ a \)) that is either empty or full with a value of type \( a \). There are two fundamental primitives to interact with \( \text{MVars} \):

\[
\begin{align*}
\text{takeMVar} &:: \text{MVar} \ a \to \text{IO} \ a \\
\text{putMVar} &:: \text{MVar} \ a \to a \to \text{IO} \ ()
\end{align*}
\]

The first empties a full location and blocks otherwise whereas the second fills an empty location and blocks otherwise. Therefore, \( \text{MVars} \) can be seen as one-place channels and the particular case of \( \text{MVar} () \) corresponds to binary semaphores.

We refer the reader to [17] for an introduction to concurrency, I/O, exceptions, and cross language interfacing (the “awkward squad”).

2.2 STM Haskell

STM Haskell [4] builds on Concurrent Haskell adding transactional actions and a transactional memory for safe thread communication, called transactional variables or \( \text{TVars} \) for short.

Transactional actions have type \( \text{STM} \ a \) and are concatenated using \( \text{STM} \) monadic “bind” combinator, akin \( \text{IO} \) actions. A transactional action remains tentative during its execution; (its effect) is exposed to the rest of the system by

\[
\text{atomically} :: \text{STM} \ a \to \text{IO} \ a
\]

which takes an STM action and delivers an I/O action that, when performed, runs the transaction guaranteeing atomicity and isolation with respect to the rest of the system.

Transactional variables have type \( \text{TVar} \ a \) where \( a \) is the type of the value held and, like \( \text{IORef}s \), are manipulated via the interface:
newTVar :: a -> STM (TVar a)
readTVar :: TVar a -> STM a
writeTVar :: TVar a -> a -> STM ()

For instance, the following code uses monadic bind to combine a read and write operation on a transactional variable and define a “transactional update”:

modifyTVar :: TVar a -> (a -> a) -> STM ()
modifyTVar var f = do
  x <- readTVar var
  writeTVar var (f x)

Then, atomically (modifyTVar x f) delivers an I/O action that applies f to the value held by x and updates x accordingly—the two steps being executed as a single atomic isolated operation.

The primitives recalled so far cover memory interaction, but STM allows also for composable blocking. In STM Haskell, blocking translates in “this thread has been scheduled too early, i.e., the right conditions are not fulfilled (yet)”. The programmer can tell the scheduler about this fact by means of the primitive:

retry :: STM a

The semantics of retry is to abort the transaction and re-run it after at least one of the transactional variables it has read from has been updated—there is no point in blindly restarting a transaction. As showed in [4], this primitive suffices to implement MVars using STM Haskell:

data MVar a = TVar (Maybe a)
takeMVar v = do
  m <- readTVar v
  case m of
    Nothing -> retry
    Just r -> writeTVar v Nothing >> return r

Thus, a value of type MVar a is a transactional variable holding a value of type Maybe a, i.e., a value which is either Nothing or actually something of type a. A thread applying takeMVar to an empty MVar is effectively blocked since it retries the transaction upon reading Nothing and then it is not rescheduled until the content of the transactional variable changes.

Finally, transactions can be composed as alternatives by means of

orElse :: STM a -> STM a -> STM a

which evaluates its first argument, and if this results is a retry the second argument is evaluated discarding any effect of the first.

3 Haskell interface for Isolated and Open transactions
In this section we give a brief overview of the interface for open transactions for Haskell. In fact, OTM can be implemented in any programming language, provided we have some means to forbid irreversible effects inside transactions; we have chosen Haskell because its typing system allows us to implement this restriction quite easily. Namely, we define two monads OTM and ITM (see Figure 1), representing the computational aspects of atomic multi-threaded open (i.e., non-isolated) transactions and atomic single-threaded isolated transactions, respectively. Transactional memory locations are values of type OTVar and can be manipulated by isolated transactional actions only.

Using the construct `atomic`, programs in the OTM monad are executed “all-or-nothing” but without isolation; hence these transactions can merge at runtime. When needed, actions inside transactions can be executed in isolation by using the construct `isolated`. Both OTM and ITM transactions are composable; we exploit Haskell type system to prevent irreversible effects inside these monads. OTM is a conservative extension (in fact, a drop-in replacement) of STM [4]: in fact, STM’s `atomically` is precisely the composition of `atomic` and `isolated` (Figure 2). This allows programmers to decide the granularity of interactions;
e.g., the snippet below combines read and write actions to define an isolated
atomic update of a transactional location.

```haskell
modifyOTVar :: OTVar a -> (a -> a) -> ITM ()
modifyOTVar var f = do
  x <- readOTVar var
  writeOTVar var (f x)
```

Invariants on transactional locations can be easily checked by composing reads
with checks that issue a retry if the invariant is not met, as in the snippet below.

```haskell
assertOTVar :: OTVar a -> (a -> Bool) -> ITM ()
assertOTVar var p = do
  x <- readOTVar var
  check (p x)

check :: Bool -> ITM ()
check b = if b then return () else retry
```

By sharing OTVars, non-isolated actions can share their view of transactional
memory and affect each other. Consistency is guaranteed by merging trans-
actions upon interaction thus the merged transaction may commit only if all
participants agree on the final state of shared OTVars.

4 Additional examples

**Semaphores** A semaphore is a counter with two fundamental operation: up which
increments the counter and down which decrements the counter if it is not zero
and blocks otherwise. Semaphores are implemented using OTM as OTVars hold-
ing a counter:

```haskell
type Semaphore = OTVar Int
```

Then, up and down are two trivial atomic and isolated updates, with the latter
being guarded by a pre-condition:

```haskell
up :: Semaphore -> ITM ()
up s = modifyOTVar s (1+)

down :: Semaphore -> ITM ()
```
down s = do
  assertOTVar s (> 0)
  modifyOTVar s (-1+)

Actions can also be composed as alternatives by means of the primitive orElse. For instance, the following takes a family of semaphores and delivers an action that decrements one of them, blocking only if none can be decremented:

\[
\text{downAny} :: \left[\text{Sempahore}\right] \rightarrow \text{ITM}() \\
\text{downAny} (x:xs) = \text{down} x \ \text{orElse} \ \text{downAny} xs \\
\text{downAny} [] = \text{retry}
\]

**Synchronisation** Let us see open transactions in action by implementing a synchronisation scenario as described in Section 1. In this example a master process outsources part of an atomic computation to some thread chosen from a worker pool; data is exchanged via some shared variable, whose access is coordinated by a pair of semaphores. Notably, both the master and the worker can abort the computation at any time, leading the other party to abort as well. This can be achieved straightforwardly using OTM:

\[
\text{master} c1 c2 = \text{do} \\
  \quad \text{-- put request} \\
  \quad \text{isolated (up c1)} \\
  \quad \text{-- do something else} \\
  \quad \text{isolated (down c2)} \\
  \quad \text{-- get answer}
\]

\[
\text{worker} c1 c2 = \text{do} \\
  \quad \text{-- do something} \\
  \quad \text{isolated (down c1)} \\
  \quad \text{-- get request} \\
  \quad \text{isolated (down c2)} \\
  \quad \text{-- put answer} \\
  \quad \text{isolated (up c2)}
\]

Both functions deliver atomic actions in OTM, and hence are not isolated. We used semaphores for the sake of exposition but we could synchronize by means of more abstract mechanisms, like barriers, channels or futures, which can be implemented using OTM as discussed in the rest of this section.

**Crowdfunding** We consider a scenario in which one party needs to atomically acquire a given number of resources which are offered by a dynamic group. For sake of exposition we rephrase the example using the metaphor of a fundraiser’s “crowdfunding campaign”: the resources to be acquired are the campaign goal and the resources are donated by a dynamically determined crowd of backers. The implementation is shown in Figure 3.

Each participant has a bank account, i.e. an OTVar holding an integer representing its balance. Accounts have two operations deposit and withdraw which are implemented along the lines of up and down, respectively; withdraw blocks until the account has enough funds. A campaign have a temporary account to store funds before transferring them to the fundraiser that closes the campaign; this operation blocks until the goal is met. Backer participants transfer a chosen amount of funds from their account to the campaign account, but the transfer is delayed until the campaign is closed. Notice that participants do not need to know each other to coordinate.
type Account = OTVar Int

type Campaign = (Account, Int)

transfer :: Account -> Account -> Int -> ITM ()
transfer a1 a2 n = do
  withdraw a1 n
  deposit a2 n

newCampaign target = do
  a <- newOTvar 0
  return (a, target)

backCampaign :: Account -> Campaign -> Int -> ITM ()
backCampaign a (a',_) k = transfer a a' k

commitCampaign :: Account -> Campaign -> ITM ()
commitCampaign a (a', t) = do
  x <- readOTVar a'
  check (x >= t)
  transfer a' a x

Figure 3: Crowdfunding.

type Barrier = OTVar (Int, Int)

newBarrier :: ITM Barrier
newBarrier = newOTVar (0,0)

join :: Barrier -> ITM ()
join b = do
  assertOTVar b nobodyWaiting
  modifyOTVar b (bimap (1+) id)

await :: Barrier -> OTM ()
await b = do
  isolated $ modifyOTVar b
  (bimap (-1+) (1+))
  isolated $ do
  assertOTVar b nobodyRunning
  modifyOTVar b (bimap id (-1+))
  nobodyRunning (r,_) = r == 0
  nobodyWaiting (_,w) = w == 0

bimap f g (a, b) = (f a, g b)

Figure 4: Thread barrier.

**Thread barriers** Barriers are abstractions used to coordinate groups of threads; once reached a barrier, threads cannot cross it until all other participants reach the barrier. Thread groups can be either dynamic or static, depending on whether threads may join the group or not. Here we consider dynamic groups.

Threads interact with barriers with `join` for joining the group associated with the barrier and with `await` for blocking waiting all participants before crossing. Barriers can be implemented using OTM in few lines as shown in Figure 4. A barrier is composed by a transactional variable holding a pair of counters tracking the number of participating threads that are waiting or running. For sake of simplicity, we prevent new joins during barrier crossing. This is enforced by the assertion guarding the counter update performed by `join`. Waiting and crossing correspond to the two isolated actions composing `await`: the first changes the state of the thread from running to waiting and the second ensures that all threads reached the barrier before crossing and decrementing the waiting counter. Differently from `join`, `await` cannot be isolated: isolation would prevent other participants from updating their state from “running” to “waiting”.

This implementation is meant as a way to coordinate concurrent transactional actions but it may be used to coordinate concurrent I/O actions as it is. The latter scenario could be implemented also using STM, but in this case `await`
would necessarily be an I/O action since it cannot be an isolated atomic action (i.e., of type $STM\ a$)—and hence, it would not be atomic either.

Atomic futures Suppose we want to delegate some task to another thread and collect the result once it is ready. An intuitive way to achieve this is by means of futures, i.e. “proxy results” that will be produced by the worker threads.

```haskell
type Future a = OTVar (Maybe a)
getFuture :: Future a -> ITM a
  getFuture f = do
    v <- readOTVar f
    case v of
      Nothing -> retry
      Just val -> return val
spawn :: OTM a -> OTM (Future a)
  spawn job = do
    future <- newOTVar Nothing
    fork (worker future)
    return future
  where
    worker :: Future a -> OTM ()
    worker future = do
      result <- job
      writeOTVar future (Just $! result)
```

Figure 5: Atomic futures.

A future can be implemented in OTM by a TVar holding a value of type $Maybe\ a$: either it is “not-ready-yet” (Nothing) or it holds something of type $a$. Future values are retrieved via $getFuture$ which takes a future and delivers an action that blocks until the value is ready and then produces the value. Futures are created by $spawn$ which takes a transactional action to be performed by a forked (transactional) thread. The complete implementation is in Figure 5.

Petri nets Petri nets are a well-known (graphical) formal model for concurrent, discrete-event dynamic systems. A Petri net is readily implemented in OTM by representing each transition by a thread, and each place by a semaphore. Putting and taking a token from a place correspond to increasing (up) or decreasing (down) its semaphore—the latter blocks if no tokens are available. Each thread repeatedly simulates the firing of the transition it represents, by taking tokens from its input places and putting tokens in its output places. These semaphore operations must be performed atomically but not in isolation; in fact, isolation would prevent transitions sharing a place to fire concurrently. Using OTM, all this is achieved in few lines:

```haskell
type Place = Semaphore

transition :: [Place] -> [Place] -> IO ThreadId
transition inputs outputs = forkIO (forever fire)
  where
    fire = atomic $ do
      mapM_ (isolated . down) inputs
      mapM_ (isolated . up) outputs
```
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Note that, since firing is atomic but not isolated, the above is an implementation of true concurrent Petri nets, which is usually more difficult to achieve than interleaving semantics.

For instance, consider the Petri net in Figure 6a, it is immediate to implement it as follows:

```haskell
main = do
    p1 <- atomically (newPlace 1)
    p2 <- atomically (newPlace 0)
    p3 <- atomically (newPlace 0)
    p4 <- atomically (newPlace 0)
    transition [p1] [p3, p4]
    transition [p1, p2] [p4]
```

Since $p_1$ has only one token either $t_1$ or $t_2$ fires. In fact, if $t_2$ acquires the token it will fail to acquire the other from $p_2$ and hence its transaction retries releasing the token and leaving it to $t_1$.

Dijkstra’s dining philosophers problem is a textbook classic of concurrency theory. This problem can be modelled using Petri nets representing each fork and philosopher as a place and as a transition respectively; the Petri net model for the 7 philosophers instance is in Figure 6b. Then, we can use the above implementation of Petri nets to simulate $k$ philosophers on $k$ threads as follows:

```haskell
philosophers k = mapM_ philosopher =<< pairs
    where
        philosopher (l,r) = transition [l,r] [l,r]
        left = satomically . sequence . take k . repeat $ newPlace 1
        right = take k . drop 1 . cycle <$> left
        pairs = zip <$> right <*> left
```

Under the assumption of fair scheduling, no execution locks.
With minor variations to transaction, the above implementation can be used to orchestrate code, using abstract models based on Petri nets.

5 Formal semantics of OTM

In this section we provide the formal semantics of OTM. Following [4], we fix an Haskell-like language extended with the OTM primitives of Figure 1 and characterise the behaviour of OTM by means of an abstract machine.

The language syntax is given by the following grammar:

Values $V ::= r | x \rightarrow M | \text{return } M | M >>= N | \text{throw } M | \text{catch } M N | \text{putChar } c | \text{getChar } | \text{fork } M | \text{atomic } M | \text{isolated } M | \text{retry } | M \text{ 'orElse' } N | \text{newOTVar } M | \text{readOTVar } r | \text{writeOTVar } r M$

Terms $M ::= x | V | M N$

where the meta-variables $x$ and $r$ range over a given countable set of variables $\text{Var}$ and of location names $\text{Loc}$, respectively. We assume Haskell typing conventions and denote the set of all well-typed terms by $\text{Term}$.

Terms are evaluated by an abstract state machine whose states are pairs $(P; \Sigma)$ formed by:

- a thread family (or process) $P = T_{t_1} \parallel \cdots \parallel T_{t_n}$ where $t_i$ are unique thread identifiers;
- a memory $\Sigma = (\Theta, \Delta, \Psi)$, where $\Theta: \text{Loc} \rightarrow \text{Term}$ is the heap and $\Delta: \text{Loc} \rightarrow \text{Term} \times \text{TrName}$ is the working memory; $\text{TrName}$ is a set of names used to identify active transactions; $\Psi$ is a forest of threads identifiers keeping track of how threads have been forked.

Threads are the smaller unit of execution the machine scheduler operates on; they evaluate OTM terms and do not have any private transactional memory. A thread $T_i$ has two forms: $(M)_i$ for threads evaluating a term $M$ outside a transaction and $(M; N)_{i,k}$ for threads evaluating $M$ inside transaction $k$ with continuation $N$ (the term to evaluate after that $k$ has committed).

As for traditional closed (ACID) transactions (e.g., [4]), operations inside a transaction are evaluated against the distributed working memory $\Delta$ and effects are propagated to the heap $\Theta$ only on commits. When a thread inside a transaction $k$ accesses a location outside $\Delta$ the location is claimed by transaction $k$ and remains claimed until $k$ commits, aborts or restarts. Threads in $k$ can interact only with locations claimed by $k$, but active transactions can be merged to share their claimed locations. We denote the set of all possible states as $\Sigma$, and reference to each projected component of $\Sigma$ by a subscript, i.e. $\Sigma_\theta$ for the heap and $\Sigma_\Delta$ for the working memory. When describing updates to the memory $\Sigma$, we adopt the convention that $\Sigma'$ has to be intended equals to $\Sigma$ except if stated otherwise, i.e. by statements like $\Sigma'_\theta = \Sigma_\theta[r \mapsto M]$. Finally, $\emptyset$ denotes the empty heap and working memory.
\[
M \not\equiv V \quad \forall [M] = V \\
\text{Eval}
\]

\[
\text{return } M \triangleright\triangleright N \rightarrow N \quad M \rightarrow \text{BindVal} \\
e \in \{\text{retry, return } N\} \\
e \triangleright\triangleright M \rightarrow e \quad \text{BindEx}
\]

\[
r \in \{\text{retry, return } N\} \\
r \not\in \{\text{catch}\} M \rightarrow r \\
\text{CatchVal} \\
\text{throw } M \not\in \{\text{catch}\} N \rightarrow N \quad M \rightarrow \text{CatchEx}
\]

Figure 7: Term reductions: \( M \rightarrow N \).

\[
\langle \mathbb{P}_i[\text{putChar}]; \Sigma \rangle \xrightarrow{\text{IsChar}} \langle \mathbb{P}_i[\text{return } c]; \Sigma \rangle \\
\langle \mathbb{P}_i[\text{return } \ell]; \Sigma \rangle \xrightarrow{\text{OutChar}} \langle \mathbb{P}_i[\text{return } \ell]; \Sigma \rangle \\
\langle \mathbb{P}_i[\text{fork } M]; \Sigma \rangle \xrightarrow{\text{TermIO}} \langle \mathbb{P}_i[\text{return } \ell'] || \{M\}; \Sigma \rangle \\
t' \not\in \text{threads}(\mathbb{P}_i[\text{fork } M]) \\
\langle \mathbb{P}_i[\text{fork } M]; \Sigma \rangle \xrightarrow{\text{TermT}} \langle \mathbb{P}_i[\text{return } \ell'] || \{M\}; \Sigma \rangle
\]

Figure 8: 10 state transitions.

\[
\langle \mathbb{T}_{t,k}[M]; \Sigma \rangle \xrightarrow{\text{ForkT}} \langle \mathbb{T}_{t,k}[N]; \Sigma \rangle \\
t' \not\in \text{threads}(\mathbb{T}_{t,k}[\text{fork } M]) \\
\langle \mathbb{T}_{t,k}[\text{fork } M]; \Sigma \rangle \xrightarrow{\text{NewVar}} \langle \mathbb{T}_{t,k}[\text{return } \ell'] || \{M\}; \Sigma \rangle \\
r \not\in \text{dom}(\Sigma_\alpha) \\
\langle \mathbb{T}_{t,k}[\text{newOTVar } M]; \Sigma \rangle \xrightarrow{\text{Read1}} \langle \mathbb{T}_{t,k}[\text{return } \ell'] || \{M\}; \Sigma \rangle \\
\langle \mathbb{T}_{t,k}[\text{newOTVar } M]; \Sigma \rangle \xrightarrow{\text{Read2}} \langle \mathbb{T}_{t,k}[\text{return } \ell'] || \{M\}; \Sigma \rangle \\
r \not\in \text{dom}(\Sigma_\alpha) \\
\langle \mathbb{T}_{t,k}[\text{writeOTVar } M]; \Sigma \rangle \xrightarrow{\text{Write1}} \langle \mathbb{T}_{t,k}[\text{return } \ell'] || \{M\}; \Sigma \rangle \\
\langle \mathbb{T}_{t,k}[\text{writeOTVar } M]; \Sigma \rangle \xrightarrow{\text{Write2}} \langle \mathbb{T}_{t,k}[\text{return } \ell'] || \{M\}; \Sigma \rangle \\
\langle \mathbb{T}_{t,k}[\text{return } \ell'] || \{M\}; \Sigma \rangle \xrightarrow{\text{Op1}} \langle \mathbb{T}_{t,k}[\text{return } \ell'] || \{M\}; \Sigma \rangle \\
\langle \mathbb{T}_{t,k}[\text{return } \ell'] || \{M\}; \Sigma \rangle \xrightarrow{\text{Op2}} \langle \mathbb{T}_{t,k}[\text{return } \ell'] || \{M\}; \Sigma \rangle
\]

Figure 9: Transactional state transitions: \( \langle P; \Sigma \rangle \xrightarrow{\cdot} \langle P'; \Sigma' \rangle \).
\[\begin{align*}
\langle \{\text{atomic } M \gg N\}; \Sigma \rangle & \xrightarrow{\text{new}(k)} \langle \{M; N\}; \Sigma \rangle \\
\Sigma'_b &= \text{commit}(k, \Sigma) \quad \Sigma'_a = \text{cleanup}(k, \Sigma) \\
\langle \{\text{return } M; N\}; t, k; \Sigma \rangle & \xrightarrow{\text{co}(k)} \langle \{\text{return } M \gg N\}; t; \Sigma' \rangle \\
\Sigma'_b &= \text{leak}(k, \Sigma) \quad \Sigma'_a = \text{cleanup}(k, \Sigma) \quad \Sigma'_\phi = \text{remove}(r, \Sigma\phi) \quad r = \text{root}(t, \Sigma\phi) \\
\langle \{\text{throw } M; N\}; t, k; \Sigma \rangle & \xrightarrow{\{\text{throw } M \gg N\}; t; \Sigma' \rangle \\
\Sigma'_b &= \text{leak}(k, \Sigma) \quad \Sigma'_a = \text{cleanup}(k, \Sigma) \quad \Sigma'_\phi = \text{remove}(r, \Sigma\phi) \\
\langle \{M'; N\}; t', k; \Sigma \rangle & \xrightarrow{\{\text{return } M \gg N\}; t'; \Sigma' \rangle \\
\Sigma'_b &= \text{leak}(k, \Sigma) \quad \Sigma'_a = \text{cleanup}(k, \Sigma) \quad \Sigma'_\phi = \text{remove}(r, \Sigma\phi) \\
\langle P; \Sigma \rangle & \xrightarrow{\text{abort}(k, t, M)} \langle P; \Sigma' \rangle \\
\langle P; \Sigma \rangle & \xrightarrow{\text{abort}(k, t, M)} \langle P'; \Sigma' \rangle \\
\langle P; \Sigma \rangle & \xrightarrow{\text{Abort}(2)} \langle P'; \Sigma' \rangle \\
\langle P; \Sigma \rangle & \xrightarrow{\text{Abort}(3)} \langle P'; \Sigma' \rangle \\
\langle P; \Sigma \rangle & \xrightarrow{\beta} \langle P'; \Sigma' \rangle \quad \beta \neq \tau \quad \text{transaction}(\beta) \notin \text{transactions}(Q) \\
\langle P; \Sigma \rangle & \xrightarrow{\beta} \langle P'; \Sigma' \rangle
\end{align*}\]

Figure 10: Transaction management transitions: \( \langle P; \Sigma \rangle \xrightarrow{\beta} \langle P'; \Sigma' \rangle \).

**Semantics** The machine dynamics is defined by the two transition relations induced by the rules in Figures 7 to 10; auxiliary definitions are in Figure 11.

The first relation \( M \rightarrow N \) is defined on terms only, and models pure computations (Figure 7). In particular, rule EVAL allows a term \( M \) that is not a value to be evaluated by means of an auxiliary (partial) function \( V[M] \) yielding the value \( V \); the other rules define the semantics of the monadic bind and exception handling in a standard way. It is interesting to notice the symmetry between bind and catch and how retry is treated as an exception by rule BINDEX and as a result value by rule CATCHVAL.

Relation \( \rightarrow \) is used to define the labelled transition relation \( \langle P; \Sigma \rangle \xrightarrow{\beta} \langle P'; \Sigma' \rangle \) over states. This relation is non deterministic, to model the fact that the scheduler can choose among various threads to execute next; therefore, several rules can apply to a given state according to different evaluation contexts:

**Expression:** \( E ::= [-] \mid E \gg M \)  \quad **Plain process:** \( P_t ::= \langle E \rangle_t \mid P \)  
**Transaction:** \( T_{t,k} ::= \langle E; M \rangle_{t,k} \parallel P \)  \quad **Any process:** \( A_t ::= P_t \mid T_{t,k} \)
threads\((T_1 \parallel \cdots \parallel T_n)\) \triangleq \{t_1, \ldots, t_n\}

transaction\((\beta)\) \triangleq k \text{ for } \beta \in \{\text{new}(k), \text{co}(k), \text{ab}(k, t, M), \overline{\text{ab}}(k, t, M)\}

\((\Delta[k \mapsto j])(r)\) \triangleq \begin{cases} \Delta(r) & \text{if } \Delta(r) = (M, l), l \neq k \hfill \text{ } \\
(M, j) & \text{if } \Delta(r) = (M, k) \end{cases}

transactions\((P)\) \triangleq \begin{cases} \text{transactions}(P_1) \cup \text{transactions}(P_2) & \text{if } P = P_1 \parallel P_2 \\
\{k\} & \text{if } P = \langle M; N \rangle_{t, k} \\
\emptyset & \text{otherwise} \end{cases}

P[k \mapsto j] \triangleq \begin{cases} P_1[k \mapsto j] \parallel P_2[k \mapsto j] & \text{if } P = P_1 \parallel P_2 \\
\langle M; N \rangle_{t, j} & \text{if } P = \langle M; N \rangle_{t, k} \\
P & \text{otherwise} \end{cases}

\Theta[r \mapsto M](s) \triangleq \begin{cases} M & \text{if } r = s \text{ then } M \text{ else } \Theta(s) \hfill \text{ } \\
\emptyset & \text{otherwise} \end{cases}

\Delta[r \mapsto (M, k)](s) \triangleq \begin{cases} (M, k) & \text{if } r = s \text{ then } (M, k) \text{ else } \Delta(s) \hfill \text{ } \\
\emptyset & \text{otherwise} \end{cases}

\text{cleanup}(k, \Sigma)(r) \triangleq \begin{cases} \Sigma & \text{if } \Sigma_\Delta(r) = (M, k) \text{ then } \bot \text{ else } \Sigma_\delta(r) \hfill \text{ } \\
\Sigma & \text{otherwise} \end{cases}

\text{commit}(k, \Sigma)(r) \triangleq \begin{cases} M & \text{if } \Sigma_\delta(r) = M \text{ or } \Sigma_\delta(r) = \bot \text{ and } \Sigma_\Delta(r) = (M, k) \hfill \text{ } \\
\emptyset & \text{otherwise} \end{cases}

\text{leak}(k, \Sigma)(r) \triangleq \begin{cases} M & \text{if } \Sigma_\delta(r) = M \text{ or } \Sigma_\delta(r) = \bot \text{ and } \Sigma_\Delta(r) = (M, k) \hfill \text{ } \\
\Sigma & \text{otherwise} \end{cases}

\begin{align*}
\beta &::= \tau \mid \text{new}(k) \mid \text{co}(k) \mid \text{ab}(k, t, M) \mid \overline{\text{ab}}(k, t, M) \mid ?c \mid !c
\end{align*}

where \(k \in \text{TrName}, M \in \text{Term}\) as usual.

Labels \(\beta\) describe the kind of transition, and are defined as follows:

\begin{align*}
\beta ::= \tau \mid \text{new}(k) \mid \text{co}(k) \mid \text{ab}(k, t, M) \mid \overline{\text{ab}}(k, t, M) \mid ?c \mid !c
\end{align*}

Transitions labelled by \(\tau\) represent internal steps of transactions, i.e., which do not need any coordination: reduction of pure terms, memory operations and thread creation (see rules in Figure 9). Reading a location falls into two cases: rule Read1 models the reading of an unclaimed location and its effect is to record the claim in \(\Delta\), while rule Read2 models the reading of a claimed location and its effect is to merge the transactions of the current thread with that claiming the location. Writes behave similarly. Rules Or1 and Or2 describe the semantics of alternative sub-transactions: if the first one retry-es the second is executed discarding any effect of the first. Rule ForkT spawns a new thread for the current transaction; a term fork \(M\) can appear inside atomic, thus allowing multi-threaded open transactions, but its use inside isolated is prevented by the type system and by the shape of rule isolated as well.

The remaining labels describe state transitions concerning the life-cycle of transactions: creation, commit, abort, and restart (see rules in Figure 10). These operations require a coordination among threads; for instance, an abort from a thread has to be propagated to every thread participating to the same transaction. This is captured in the semantics by labelling the transition with the operation and the name of the transaction involved; this information is used to force
synchronisation of all participants of that transaction. To illustrate this mechanism, we describe the commit of a transaction \( k \), namely \( \langle P; \Sigma \rangle \xrightarrow{\text{commit}(k)} \langle P'; \Sigma' \rangle \).

First, by means of rule MCastGroup we split \( P \) into two subprocesses, one of which contains all threads participating in \( k \) (those not in \( k \) cannot do a transition whose label contains \( k \)). Secondly, using recursively rule MCastCo we single out every thread in \( k \). Finally, we apply rule \text{Commit} provided that every thread is ready to commit, i.e., it is of the form \( \langle \text{return } M; N \rangle_{t,k} \).

Aborting a transaction works similarly, but it is based on vetoes instead of an unanimous vote. Aborts are triggered by unhandled exceptions raised by some thread, but threads react to this situation in different ways:

- threads forked within the transaction, in the same tree of the thread raising the exception: these threads are killed (and the root thread aborted) because their creation must be discarded, as for any transactional side-effect;
- threads from different trees which joined the transaction after it was created, due to a merging: these threads just retry their transaction, since aborting would require them to handle exceptions raised by “foreign” threads.

Like Haskell STM\[4\], aborts leak some effects namely any transactional variable created in the aborted transaction that also occurs in the aborting exception.

Note that there are no derivation rules for retry: its meaning is to inform the scheduler that we have reached a state where the execution is stuck; hence the machine has to re-execute the transaction from the beginning (or backtracking from a suitable check-point), possibly following a different execution order.

6 Opacity

In this section we validate the formal semantics of OTM by proving it satisfies the opacity correctness criterion for transactional memory \[3\].

The opacity correctness criterion is an extension of the classical serialisability property for databases with the additional requirement that even non-committed transactions must access consistent states. Intuitively, this property ensures that:

1. effects of any committed transaction appear performed at a single, indivisible point during the transaction lifetime;
2. updates of any aborted transaction cannot be seen by other transactions;
3. transactions always access consistent states of the system.

In order to formally capture these intuitive requirements let us recall some notions from \[3\]. A history is a sequence of read, write, commit, and abort operations ordered according to the time at which they were issued (simultaneous

\[3\] The definition in \[3\] considers finer-grained events; in particular, read and write operations are formed by request, execution, and response events. However in loc. cit. the authors restrict to histories where request-execution-response sequences are not interleaved, hence we can consider the simpler read/writes events in the first place.
events are arbitrarily ordered) and such that no operation can be issued by a transaction that has already performed a commit or an abort. A transaction $k$ is said to be in a history $H$ if the latter contains at least one operation issued by $k$. Histories that differ only for the relative position of operations in different transactions are considered equivalent. Any history $H$ defines a happens-before partial order $\prec_H$ over transactions, where $k \prec_H k'$ iff the transaction $k$ becomes committed or aborted in $H$ before $k'$ issues its first operation. If $\prec_H$ is total then $H$ is called sequential. For a history $H$, let $\text{complete}(H)$ be the set of histories obtained by adding either a commit or an abort for every live transaction in $H$.

We can now recall Guerraoui-Kapałka’s definition of opacity [3, Def. 1].

**Definition 6.1 (Opacity).** A history $H$ is said to be opaque if there exists a sequential history $S$ equivalent to some history in $\text{complete}(H)$ such that $S$ preserves the happens-before order of $H$.

As shown in [3], opacity corresponds to the absence of mutual dependencies between live transactions, where a dependency is created whenever a transaction reads an information written by another or depends from its outcome.

**Definition 6.2 (Opacity graph [3, Sec. 5.4]).** For a history $H$ let $\ll$ be a total order on the set $T$ of all transactions in $H$. An opacity graph $\text{OPG}(H, \ll)$ is a bi-coloured directed graph on $T$ such that a vertex is red if the corresponding transaction is either running or aborted, it is black otherwise, and for all vertices $k, k' \in T$, there is an edge $k \rightarrow k'$ if any of the following holds:

1. $k'$ happens-before $k$ ($k' \prec_H k$);
2. $k$ reads something written by $k'$;
3. $k'$ reads some location written by $k$ and $k' \ll k$;
4. $k'$ is neither running nor aborted and there are a location $r$ and a transaction $k''$ such that $k' \ll k''$, $k'$ writes to $r$, and $k''$ reads $r$ from $k$.

The edge is red if the second case applies, otherwise it is black. The graph is said to be well-formed if all edges from red nodes in $\text{OPG}(H, \ll)$ are also red.

Let $H$ be a history and let $k$ be a transaction appearing in it. A read operation by $k$ is said to be local (to $k$) whenever the previous operation by $k$ on the same location was a write. A write operation by $k$ is said to be local (to $k$) whenever the next operation by $k$ on the same location is a write. We denote by $\text{nonlocal}(H)$ the longest sub-history of $H$ without any local operations. A history $H$ is said locally-consistent if every local read is preceded by a write operation that writes the read value; it is said consistent if, additionally, whenever some $k$ reads $v$ from $r$ in $\text{nonlocal}(H)$ then some $k'$ writes $v$ to $r$ in $\text{nonlocal}(H)$.

**Theorem 6.1 ([3, Thm. 2]).** A history $H$ is opaque if and only if

1. $H$ is consistent and

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*The original definition requires the history $H$ to be “legal”, but this notion is relevant only in presence of non-transactional operations which OTM prevents by design.*
2. there exists a total order $\ll$ on the set of transactions in $H$ such that $OPG(\text{nonlocal}(H), \ll)$ is well-formed and acyclic.

In [3] transactions may encapsulate several threads but cannot be merged. Therefore, in order to study opacity of OTM we extend the set of operations considered in loc. cit. with explicit merges. Let $k, k'$ be two running transactions in the given history; when they merge, they share their threads, locations, and effects. From this perspective, $k$ is commit-pending and depends from $k'$ and hence in the opacity graph, $k$ is a red node connected to $k'$ by a red edge. Hence, merges can be equivalently expressed at the history level by sequences like:

1. new $x$; 2. $k'$ writes on $x$; 3. $k$ reads from $x$; 4. $k$ prepares to commit.

These are the only dependencies found in histories generated by OTM.

**Theorem 6.2.** For $H$ a history describing an execution of a OTM program and a total order $\ll$, $OPG(\text{nonlocal}(H), \ll)$ is a forest of red edges where only roots may be black.

**Proof.** By inspection of the rules it is easy to see that (a) transactions may access only locations they claimed; (b) claimed locations are released only on commits, aborts and retries; (c) transactions have to merge with any transaction holding a location they need. Therefore, at any given time there is at most one running transaction issuing operations on a given location, hence reads and writes do not create edges. Thus edges are created only during the execution of merges and, by inspecting the above implementation, it easy to see that (d) any transaction can issue at most one merge; (e) a transaction issuing a merge is a red node; (f) the edge created by a merge is red. Therefore, transactions form a forest made of red edges where any non-root node is red.

Since a forest formed by red edges whose sources are always red is always acyclic and well-formed, we can conclude our correctness result:

**Corollary 6.1 (Opacity).** OTM meets the opacity criterion.

7 Conclusions and future work

In this paper we have presented OTM, a programming model supporting interactions between composable memory transactions. This model separates isolated transactions from non-isolated ones, still guaranteeing atomicity; the latter can interact by accessing to shared variables. Consistency is ensured by transparently merging interacting transactions at runtime. We have given a formal semantics for OTM, and proved that this model satisfies the important opacity criterion.

As future work, it would be interesting to add some heuristics to better handle retry events. Currently, a retry restarts all threads participating to the transaction; a more efficient implementation would keep track of the working set of each thread, and at a retry we need to restart only the threads whose working sets have non-empty intersection with that being restarted. Another
optimization is to implement transactions and OTVars directly in the runtime, akin the implementation of STM in the Glasgow Haskell Compiler [4].

We have presented OTM within Haskell (especially to leverage its type system), but this model is general and can be applied to other languages. A possible future work is to port this model to an imperative oriented language, such as Java or C++; however, like other TM implementations, we expect that this extension will require some changes in the compiler and/or the runtime.

This work builds on the calculus with shared memory and open transactions described in [14]. In loc. cit. this model is shown to be expressive enough to represent $TCCS^m$ [7], a variant of the Calculus of Communicating Systems with transactional synchronization. Being based on CCS, communication in $TCCS^m$ is synchronous; however, nowadays asynchronous models play an important rôle (see actors, event-driven programming, etc.), so it may be interesting to generalize the discussion so as to consider also this case, e.g. by defining an a calculus for event-driven models or an actor-based calculus with open transactions. Such a calculus can be quite useful also for modelling speculative reasoning for cooperating systems [10–13] or study distributed interacting transactions in serverless computing [2, 6, 16]. A local version of actor-based open transactions can be implemented in OTM using lock-free data structures (e.g., message queues) in shared transactional memory.

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