The GNU Transactional Memory Library

Short Contents

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1 Enabling libitm

To activate support for TM in C/C++, the compile-time flag `-fgnu-tm` must be specified. This enables TM language-level constructs such as transaction statements (e.g., `__transaction_atomic`, see Chapter 2 [C/C++ Language Constructs for TM], page 3, for details).

2 C/C++ Language Constructs for TM

Transactions are supported in C++ and C in the form of transaction statements, transaction expressions, and function transactions. In the following example, both `a` and `b` will be read and the difference will be written to `c`, all atomically and isolated from other transactions:

```
__transaction_atomic { c = a - b; }
```

Therefore, another thread can use the following code to concurrently update `b` without ever causing `c` to hold a negative value (and without having to use other synchronization constructs such as locks or C++11 atomics):

```
__transaction_atomic { if (a > b) b++; }
```

GCC follows the Draft Specification of Transactional Language Constructs for C++ (v1.1) (`https://sites.google.com/site/tmforcplusplus/`) in its implementation of transactions.

The precise semantics of transactions are defined in terms of the C++11/C11 memory model (see the specification). Roughly, transactions provide synchronization guarantees that are similar to what would be guaranteed when using a single global lock as a guard for all transactions. Note that like other synchronization constructs in C/C++, transactions rely on a data-race-free program (e.g., a nontransactional write that is concurrent with a transactional read to the same memory location is a data race).

3 The libitm ABI

The ABI provided by libitm is basically equal to the Linux variant of Intel's current TM ABI specification document (Revision 1.1, May 6 2009) but with the differences listed in this chapter. It would be good if these changes would eventually be merged into a future version of this specification. To ease look-up, the following subsections mirror the structure of this specification.

3.1 [No changes] Objectives

3.2 [No changes] Non-objectives

3.3 Library design principles

3.3.1 [No changes] Calling conventions

3.3.2 [No changes] TM library algorithms

3.3.3 [No changes] Optimized load and store routines

3.3.4 [No changes] Aligned load and store routines

3.3.5 Data logging functions

The memory locations accessed with transactional loads and stores and the memory locations whose values are logged must not overlap. This required separation only extends to the scope of the execution of one transaction including all the executions of all nested transactions.

The compiler must be consistent (within the scope of a single transaction) about which memory locations are shared and which are not shared with other threads (i.e., data must be accessed either transactionally or nontransactionally). Otherwise, non-write-through TM algorithms would not work.

For memory locations on the stack, this requirement extends to only the lifetime of the stack frame that the memory location belongs to (or the lifetime of the transaction, whichever is shorter). Thus, memory that is reused for several stack frames could be target of both data logging and transactional accesses; however, this is harmless because these stack frames' lifetimes will end before the transaction finishes.

3.3.6 [No changes] Scatter/gather calls

3.3.7 [No changes] Serial and irrevocable mode

3.3.8 [No changes] Transaction descriptor

3.3.9 Store allocation

There is no `getTransaction` function.

3.3.10 [No changes] Naming conventions

3.3.11 Function pointer encryption

Currently, this is not implemented.

3.4 Types and macros list

`_ITM_codeProperties` has changed, see [Starting a transaction], page 6. `_ITM_srcLocation` is not used.

3.5 Function list

3.5.1 Initialization and finalization functions

These functions are not part of the ABI.

3.5.2 [No changes] Version checking

3.5.3 [No changes] Error reporting

3.5.4 [No changes] inTransaction call

3.5.5 State manipulation functions

There is no `getTransaction` function. Transaction identifiers for nested transactions will be ordered but not necessarily sequential (i.e., for a nested transaction's identifier *IN* and its enclosing transaction's identifier *IE*, it is guaranteed that $IN >= IE$).

3.5.6 [No changes] Source locations

3.5.7 Starting a transaction

3.5.7.1 Transaction code properties

The bit `hasNoXMMUpdate` is instead called `hasNoVectorUpdate`. Iff it is set, vector register save/restore is not necessary for any target machine.

The `hasNoFloatUpdate` bit (`0x0010`) is new. Iff it is set, floating point register save/restore is not necessary for any target machine.

`undoLogCode` is not supported and a fatal runtime error will be raised if this bit is set. It is not properly defined in the ABI why barriers other than undo logging are not present; Are they not necessary (e.g., a transaction operating purely on thread-local data) or have they been omitted by the compiler because it thinks that some kind of global synchronization (e.g., serial mode) might perform better? The specification suggests that the latter might be the case, but the former seems to be more useful.

The `readOnly` bit (`0x4000`) is new. **TODO** Lexical or dynamic scope?

`hasNoRetry` is not supported. If this bit is not set, but `hasNoAbort` is set, the library can assume that transaction rollback will not be requested.

It would be useful if the absence of externally-triggered rollbacks would be reported for the dynamic scope as well, not just for the lexical scope (`hasNoAbort`). Without this, a library cannot exploit this together with flat nesting.

`exceptionBlock` is not supported because exception blocks are not used.

3.5.7.2 [No changes] Windows exception state

3.5.7.3 [No changes] Other machine state

3.5.7.4 [No changes] Results from beginTransaction

3.5.8 Aborting a transaction

`_ITM_rollbackTransaction` is not supported. `_ITM_abortTransaction` is supported but the abort reasons `exceptionBlockAbort`, `TMConflict`, and `userRetry` are not supported. There are no exception blocks in general, so the related cases also do not have to be considered. To encode `__transaction_cancel [[outer]]`, compilers must set the new `outerAbort` bit (`0x10`) additionally to the `userAbort` bit in the abort reason.

3.5.9 Committing a transaction

The exception handling (EH) scheme is different. The Intel ABI requires the `_ITM_tryCommitTransaction` function that will return even when the commit failed and will have to be matched with calls to either `_ITM_abortTransaction` or `_ITM_commitTransaction`. In contrast, gcc relies on transactional wrappers for the functions of the Exception Handling ABI and on one additional commit function (shown below). This allows the TM to keep track of EH internally and thus it does not have to embed the cleanup of EH state into the existing EH code in the program. `_ITM_tryCommitTransaction` is not supported. `_ITM_commitTransactionToId` is also not supported because the propagation of thrown exceptions will not bypass commits of nested transactions.

```
void _ITM_commitTransactionEH(void *exc_ptr) ITM_REGPARM;
void *_ITM_cxa_allocate_exception (size_t);
void _ITM_cxa_free_exception (void *exc_ptr);
void _ITM_cxa_throw (void *obj, void *tinfo, void (*dest) (void *));
void *_ITM_cxa_begin_catch (void *exc_ptr);
void _ITM_cxa_end_catch (void);
```

The EH scheme changed in version 6 of GCC. Previously, the compiler added a call to `_ITM_commitTransactionEH` to commit a transaction if an exception could be in flight at this position in the code; `exc_ptr` is the address of the current exception and must be non-zero. Now, the compiler must catch all exceptions that are about to be thrown out of a transaction and call `_ITM_commitTransactionEH` from the catch clause, with `exc_ptr` being zero.

Note that the old EH scheme never worked completely in GCC's implementation; libitm currently does not try to be compatible with the old scheme.

The `_ITM_cxa...` functions are transactional wrappers for the respective `__cxa...` functions and must be called instead of these in transactional code. `_ITM_cxa_free_exception` is new in GCC 6.

To support this EH scheme, libstdc++ needs to provide one additional function (_cxa_tm_cleanup), which is used by the TM to clean up the exception handling state while rolling back a transaction:

```
void __cxa_tm_cleanup (void *unthrown_obj, void *cleanup_exc,
                       unsigned int caught_count);
```

Since GCC 6, `unthrown_obj` is not used anymore and always null; prior to that, `unthrown_obj` is non-null if the program called `__cxa_allocate_exception` for this exception but did not yet called `__cxa_throw` for it. `cleanup_exc` is non-null if the program is currently processing a cleanup along an exception path but has not caught this exception yet. `caught_count` is the nesting depth of `__cxa_begin_catch` within the transaction (which can be counted by the TM using `_ITM_cxa_begin_catch` and `_ITM_cxa_end_catch`); `__cxa_tm_cleanup` then performs rollback by essentially performing `__cxa_end_catch` that many times.

3.5.10 Exception handling support

Currently, there is no support for functionality like `__transaction_cancel throw` as described in the C++ TM specification. Supporting this should be possible with the EH scheme explained previously because via the transactional wrappers for the EH ABI, the TM is able to observe and intercept EH.

3.5.11 [No changes] Transition to serial–irrevocable mode

3.5.12 [No changes] Data transfer functions

3.5.13 [No changes] Transactional memory copies

3.5.14 Transactional versions of memmove

If either the source or destination memory region is to be accessed nontransactionally, then source and destination regions must not be overlapping. The respective `_ITM_memmove` functions are still available but a fatal runtime error will be raised if such regions do overlap. To support this functionality, the ABI would have to specify how the intersection of the regions has to be accessed (i.e., transactionally or nontransactionally).

3.5.15 [No changes] Transactional versions of memset

3.5.16 [No changes] Logging functions

3.5.17 User-registered commit and undo actions

Commit actions will get executed in the same order in which the respective calls to `_ITM_addUserCommitAction` happened. Only `_ITM_noTransactionId` is allowed as value for the `resumingTransactionId` argument. Commit actions get executed after privatization safety has been ensured.

Undo actions will get executed in reverse order compared to the order in which the respective calls to `_ITM_addUserUndoAction` happened. The ordering of undo actions w.r.t. the roll-back of other actions (e.g., data transfers or memory allocations) is undefined.

`_ITM_getThreadnum` is not supported currently because its only purpose is to provide a thread ID that matches some assumed performance tuning output, but this output is not part of the ABI nor further defined by it.

`_ITM_dropReferences` is not supported currently because its semantics and the intention behind it is not entirely clear. The specification suggests that this function is necessary because of certain orderings of data transfer undos and the releasing of memory regions (i.e., privatization). However, this ordering is never defined, nor is the ordering of dropping references w.r.t. other events.

3.5.18 [New] Transactional indirect calls

Indirect calls (i.e., calls through a function pointer) within transactions should execute the transactional clone of the original function (i.e., a clone of the original that has been fully instrumented to use the TM runtime), if such a clone is available. The runtime provides two functions to register/deregister clone tables:

```
struct clone_entry
{
  void *orig, *clone;
};

void _ITM_registerTMCloneTable (clone_entry *table, size_t entries);
void _ITM_deregisterTMCloneTable (clone_entry *table);
```

Registered tables must be writable by the TM runtime, and must be live throughout the life-time of the TM runtime.

TODO The intention was always to drop the registration functions entirely, and create a new ELF Phdr describing the linker-sorted table. Much like what currently happens for `PT_GNU_EH_FRAME`. This work kept getting bogged down in how to represent the *N* different code generation variants. We clearly needed at least two—SW and HW transactional clones—but there was always a suggestion of more variants for different TM assumptions/invariants.

The compiler can then use two TM runtime functions to perform indirect calls in transactions:

```
void *_ITM_getTMCloneOrIrrevocable (void *function) ITM_REGPARM;
void *_ITM_getTMCloneSafe (void *function) ITM_REGPARM;
```

If there is a registered clone for supplied function, both will return a pointer to the clone. If not, the first runtime function will attempt to switch to serial–irrevocable mode and return the original pointer, whereas the second will raise a fatal runtime error.

3.5.19 [New] Transactional dynamic memory management

```
void *_ITM_malloc (size_t)
       __attribute__((__malloc__)) ITM_PURE;
void *_ITM_calloc (size_t, size_t)
       __attribute__((__malloc__)) ITM_PURE;
void _ITM_free (void *) ITM_PURE;
```

These functions are essentially transactional wrappers for `malloc`, `calloc`, and `free`. Within transactions, the compiler should replace calls to the original functions with calls to the wrapper functions.

libitm also provides transactional clones of C++ memory management functions such as global operator new and delete. They are part of libitm for historic reasons but do not need to be part of this ABI.

3.6 [No changes] Future Enhancements to the ABI

3.7 Sample code

The code examples might not be correct w.r.t. the current version of the ABI, especially everything related to exception handling.

3.8 [New] Memory model

The ABI should define a memory model and the ordering that is guaranteed for data transfers and commit/undo actions, or at least refer to another memory model that needs to be preserved. Without that, the compiler cannot ensure the memory model specified on the level of the programming language (e.g., by the C++ TM specification).

For example, if a transactional load is ordered before another load/store, then the TM runtime must also ensure this ordering when accessing shared state. If not, this might break the kind of publication safety used in the C++ TM specification. Likewise, the TM runtime must ensure privatization safety.

4 Internals

4.1 TM methods and method groups

libitm supports several ways of synchronizing transactions with each other. These TM methods (or TM algorithms) are implemented in the form of subclasses of `abi_dispatch`, which provide methods for transactional loads and stores as well as callbacks for rollback and commit. All methods that are compatible with each other (i.e., that let concurrently running transactions still synchronize correctly even if different methods are used) belong to the same TM method group. Pointers to TM methods can be obtained using the factory methods prefixed with `dispatch_` in `libitm_i.h`. There are two special methods, `dispatch_serial` and `dispatch_serialirr`, that are compatible with all methods because they run transactions completely in serial mode.

4.1.1 TM method life cycle

The state of TM methods does not change after construction, but they do alter the state of transactions that use this method. However, because per-transaction data gets used by several methods, `gtm_thread` is responsible for setting an initial state that is useful for all methods. After that, methods are responsible for resetting/clearing this state on each rollback or commit (of outermost transactions), so that the transaction executed next is not affected by the previous transaction.

There is also global state associated with each method group, which is initialized and shut down (`method_group::init()` and `fini()`) when switching between method groups (see `retry.cc`).

4.1.2 Selecting the default method

The default method that libitm uses for freshly started transactions (but not necessarily for restarted transactions) can be set via an environment variable (`ITM_DEFAULT_METHOD`), whose value should be equal to the name of one of the factory methods returning abi_dispatch subclasses but without the "dispatch_" prefix (e.g., "serialirr" instead of `GTM::dispatch_serialirr()`).

Note that this environment variable is only a hint for libitm and might not be supported in the future.

4.2 Nesting: flat vs. closed

We support two different kinds of nesting of transactions. In the case of *flat nesting*, the nesting structure is flattened and all nested transactions are subsumed by the enclosing transaction. In contrast, with *closed nesting*, nested transactions that have not yet committed can be rolled back separately from the enclosing transactions; when they commit, they are subsumed by the enclosing transaction, and their effects will be finally committed when the outermost transaction commits. *Open nesting* (where nested transactions can commit independently of the enclosing transactions) are not supported.

Flat nesting is the default nesting mode, but closed nesting is supported and used when transactions contain user-controlled aborts (`__transaction_cancel` statements). We assume that user-controlled aborts are rare in typical code and used mostly in exceptional situations. Thus, it makes more sense to use flat nesting by default to avoid the performance overhead of the additional checkpoints required for closed nesting. User-controlled aborts will correctly abort the innermost enclosing transaction, whereas the whole (i.e., outermost) transaction will be restarted otherwise (e.g., when a transaction encounters data conflicts during optimistic execution).

4.3 Locking conventions

This section documents the locking scheme and rules for all uses of locking in libitm. We have to support serial(-irrevocable) mode, which is implemented using a global lock as explained next (called the *serial lock*). To simplify the overall design, we use the same lock as catch-all locking mechanism for other infrequent tasks such as (de)registering clone tables or threads. Besides the serial lock, there are *per-method-group locks* that are managed by specific method groups (i.e., groups of similar TM concurrency control algorithms), and lock-like constructs for quiescence-based operations such as ensuring privatization safety.

Thus, the actions that participate in the libitm-internal locking are either *active transactions* that do not run in serial mode, *serial transactions* (which (are about to) run in serial mode), and management tasks that do not execute within a transaction but have acquired the serial mode like a serial transaction would do (e.g., to be able to register threads with libitm). Transactions become active as soon as they have successfully used the serial lock to announce this globally (see [Serial lock implementation], page 14). Likewise, transactions become serial transactions as soon as they have acquired the exclusive rights provided by the serial lock (i.e., serial mode, which also means that there are no other concurrent active or serial transactions). Note that active transactions can become serial transactions when they enter serial mode during the runtime of the transaction.

4.3.1 State-to-lock mapping

Application data is protected by the serial lock if there is a serial transaction and no concurrently running active transaction (i.e., non-serial). Otherwise, application data is protected by the currently selected method group, which might use per-method-group locks or other mechanisms. Also note that application data that is about to be privatized might not be allowed to be accessed by nontransactional code until privatization safety has been ensured; the details of this are handled by the current method group.

libitm-internal state is either protected by the serial lock or accessed through custom concurrent code. The latter applies to the public/shared part of a transaction object and most typical method-group-specific state.

The former category (protected by the serial lock) includes:

- The list of active threads that have used transactions.
- The tables that map functions to their transactional clones.
- The current selection of which method group to use.
- Some method-group-specific data, or invariants of this data. For example, resetting a method group to its initial state is handled by switching to the same method group, so the serial lock protects such resetting as well.

In general, such state is immutable whenever there exists an active (non-serial) transaction. If there is no active transaction, a serial transaction (or a thread that is not currently executing a transaction but has acquired the serial lock) is allowed to modify this state (but must of course be careful to not surprise the current method group's implementation with such modifications).

4.3.2 Lock acquisition order

To prevent deadlocks, locks acquisition must happen in a globally agreed-upon order. Note that this applies to other forms of blocking too, but does not necessarily apply to lock acquisitions that do not block (e.g., trylock() calls that do not get retried forever). Note that serial transactions are never return back to active transactions until the transaction has committed. Likewise, active transactions stay active until they have committed. Per-method-group locks are typically also not released before commit.

Lock acquisition / blocking rules:

- Transactions must become active or serial before they are allowed to use method-group-specific locks or blocking (i.e., the serial lock must be acquired before those other locks, either in serial or nonserial mode).
- Any number of threads that do not currently run active transactions can block while trying to get the serial lock in exclusive mode. Note that active transactions must not block when trying to upgrade to serial mode unless there is no other transaction that is trying that (the latter is ensured by the serial lock implementation.
- Method groups must prevent deadlocks on their locks. In particular, they must also be prepared for another active transaction that has acquired method-group-specific locks but is blocked during an attempt to upgrade to being a serial transaction. See below for details.
- Serial transactions can acquire method-group-specific locks because there will be no other active nor serial transaction.

There is no single rule for per-method-group blocking because this depends on when a TM method might acquire locks. If no active transaction can upgrade to being a serial transaction after it has acquired per-method-group locks (e.g., when those locks are only acquired during an attempt to commit), then the TM method does not need to consider a potential deadlock due to serial mode.

If there can be upgrades to serial mode after the acquisition of per-method-group locks, then TM methods need to avoid those deadlocks:

- When upgrading to a serial transaction, after acquiring exclusive rights to the serial lock but before waiting for concurrent active transactions to finish (see [Serial lock implementation], page 14, for details), we have to wake up all active transactions waiting on the upgrader's per-method-group locks.
- Active transactions blocking on per-method-group locks need to check the serial lock and abort if there is a pending serial transaction.
- Lost wake-ups have to be prevented (e.g., by changing a bit in each per-method-group lock before doing the wake-up, and only blocking on this lock using a futex if this bit is not group).

TODO: Can reuse serial lock for gl-*? And if we can, does it make sense to introduce further complexity in the serial lock? For gl-*, we can really only avoid an abort if we do -wb and -vbv.

4.3.3 Serial lock implementation

The serial lock implementation is optimized towards assuming that serial transactions are infrequent and not the common case. However, the performance of entering serial mode can matter because when only few transactions are run concurrently or if there are few threads, then it can be efficient to run transactions serially.

The serial lock is similar to a multi-reader-single-writer lock in that there can be several active transactions but only one serial transaction. However, we do want to avoid contention (in the lock implementation) between active transactions, so we split up the reader side of the lock into per-transaction flags that are true iff the transaction is active. The exclusive writer side remains a shared single flag, which is acquired using a CAS, for example. On the fast-path, the serial lock then works similar to Dekker's algorithm but with several reader flags that a serial transaction would have to check. A serial transaction thus requires a list of all threads with potentially active transactions; we can use the serial lock itself to protect this list (i.e., only threads that have acquired the serial lock can modify this list).

We want starvation-freedom for the serial lock to allow for using it to ensure progress for potentially starved transactions (see [Progress Guarantees], page 15, for details). However, this is currently not enforced by the implementation of the serial lock.

Here is pseudo-code for the read/write fast paths of acquiring the serial lock (read-to-write upgrade is similar to write_lock:

```
// read_lock:
tx->shared_state |= active;
__sync_synchronize(); // or STLD membar, or C++0x seq-cst fence
while (!serial_lock.exclusive)
  if (spinning_for_too_long) goto slowpath;

// write_lock:
if (CAS(&serial_lock.exclusive, 0, this) != 0)
  goto slowpath; // writer-writer contention
// need a membar here, but CAS already has full membar semantics
bool need_blocking = false;
for (t: all txns)
  {
    for (;t->shared_state & active;)
      if (spinning_for_too_long) { need_blocking = true; break; }
  }
if (need_blocking) goto slowpath;
```

Releasing a lock in this spin-lock version then just consists of resetting `tx->shared_state` to inactive or clearing `serial_lock.exclusive`.

However, we can't rely on a pure spinlock because we need to get the OS involved at some time (e.g., when there are more threads than CPUs to run on). Therefore, the real implementation falls back to a blocking slow path, either based on pthread mutexes or Linux futexes.

4.3.4 Reentrancy

libitm has to consider the following cases of reentrancy:

- Transaction calls unsafe code that starts a new transaction: The outer transaction will become a serial transaction before executing unsafe code. Therefore, nesting within serial transactions must work, even if the nested transaction is called from within uninstrumented code.
- Transaction calls either a transactional wrapper or safe code, which in turn starts a new transaction: It is not yet defined in the specification whether this is allowed. Thus, it is undefined whether libitm supports this.
- Code that starts new transactions might be called from within any part of libitm: This kind of reentrancy would likely be rather complex and can probably be avoided. Therefore, it is not supported.

4.3.5 Privatization safety

Privatization safety is ensured by libitm using a quiescence-based approach. Basically, a privatizing transaction waits until all concurrent active transactions will either have finished (are not active anymore) or operate on a sufficiently recent snapshot to not access the privatized data anymore. This happens after the privatizing transaction has stopped being an active transaction, so waiting for quiescence does not contribute to deadlocks.

In method groups that need to ensure publication safety explicitly, active transactions maintain a flag or timestamp in the public/shared part of the transaction descriptor. Before blocking, privatizers need to let the other transactions know that they should wake up the privatizer.

TODO Ho to implement the waiters? Should those flags be per-transaction or at a central place? We want to avoid one wake/wait call per active transactions, so we might want to use either a tree or combining to reduce the syscall overhead, or rather spin for a long amount of time instead of doing blocking. Also, it would be good if only the last transaction that the privatizer waits for would do the wake-up.

4.3.6 Progress guarantees

Transactions that do not make progress when using the current TM method will eventually try to execute in serial mode. Thus, the serial lock's progress guarantees determine the progress guarantees of the whole TM. Obviously, we at least need deadlock-freedom for the serial lock, but it would also be good to provide starvation-freedom (informally, all threads will finish executing a transaction eventually iff they get enough cycles).

However, the scheduling of transactions (e.g., thread scheduling by the OS) also affects the handling of progress guarantees by the TM. First, the TM can only guarantee deadlock-freedom if threads do not get stopped. Likewise, low-priority threads can starve if they do not get scheduled when other high-priority threads get those cycles instead.

If all threads get scheduled eventually, correct lock implementations will provide deadlock-freedom, but might not provide starvation-freedom. We can either enforce the latter in the TM's lock implementation, or assume that the scheduling is sufficiently random to yield a probabilistic guarantee that no thread will starve (because eventually, a transaction will encounter a scheduling that will allow it to run). This can indeed work well in practice but is not necessarily guaranteed to work (e.g., simple spin locks can be pretty efficient).

Because enforcing stronger progress guarantees in the TM has a higher runtime overhead, we focus on deadlock-freedom right now and assume that the threads will get scheduled eventually by the OS (but don't consider threads with different priorities). We should support starvation-freedom for serial transactions in the future. Everything beyond that is highly related to proper contention management across all of the TM (including with TM method to choose), and is future work.

TODO Handling thread priorities: We want to avoid priority inversion but it's unclear how often that actually matters in practice. Workloads that have threads with different priorities will likely also require lower latency or higher throughput for high-priority threads. Therefore, it probably makes not that much sense (except for eventual progress guarantees) to use priority inheritance until the TM has priority-aware contention management.

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