Programming Languages

Concurrency: Transactions

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Abstraction and Concurrency

Two fundamental concepts to build larger software are:

- **abstraction**: an object storing certain data and providing certain functionality may be used without reference to its internals
- **composition**: several objects can be combined to a new object without interference

Both, abstraction and composition are closely related, since the ability to compose depends on the ability to abstract from details.

Consider an example:

- a linked list data structure exposes a fixed set of operations to modify the list structure, such as `push()` and `forAll()`
- a set object may internally use the list object and expose a set of operations, including `push()`

The `insert()` operations uses the `forAll()` operation to check if the element already exists and uses `push()` if not.

Wrapping the linked list in a mutex does not help to make the set thread-safe.

⇒ wrap the two calls in `insert()` in a mutex
⇒ but other list operations can still be called ⇒ use the same mutex
⇒ unlike sequential algorithms, thread-safe algorithms cannot always be composed to give new thread-safe algorithms
Transactional Memory [2]

**Idea:** automatically convert atomic blocks into code that ensures atomic execution of the statements.

```java
atomic {
    // code
    if (cond) retry;
    atomic {
        // more code
    }
    // code
}
```

Execute code as **transaction**:

- execute the code of an atomic block
- nested atomic blocks act like a single atomic block
- check that it runs without *conflicts* due to accesses from another thread
- if another thread interferes through conflicting updates:
  - undo the computation done so far
  - re-start the transaction
- provide a *retry* keyword similar to the *wait* of monitors
Semantics of Transactions

The goal is to use transactions to specify *atomic executions*. Transactions are rooted in databases where they have the *ACID* properties:

- **atomicity**: a transaction completes or seems not to have run
  \[\implies\text{we call this} \text{ failure atomicity} \text{ to distinguish it from atomic executions}\]

- **consistency**: each transaction transforms a consistent state to another consistent state
  - a consistent state is one in which certain *invariants* hold
  - invariants depend on the application

- **isolation**: transactions do not interfere with each other
  \[\implies\text{not so evident with respect to non-transactional memory}\]

- **durability**: the effects are permanent ✓

Transactions themselves must be *serializable*:

- the result of running concurrent transactions must be identical to *one* execution of them in sequence
- serializability for transactions is insufficient to perform synchronization between threads
Consistency During Transactions

Consistency during a transaction.

ACID states how committed transactions behave but not what may happen until a transaction commits.

- a transaction that is run on an inconsistent state may generate an inconsistent state → zombie transaction
- in the best case, the zombie transaction will be aborted eventually
- but transactions may cause havoc when run on inconsistent states

atomic {
    int tmp1 = x;
    int tmp2 = y;
    assert(tmp1-tmp2==0);
}

// preserved invariant: x==y

atomic {
    x = 10;
    y = 10;
}

⚠️ critical for null pointer derefs or divisions by zero, e.g.

Definition (opacity)

A TM system provides opacity if failing transactions are serializable w.r.t. committing transactions.

⇝ failing transactions still see a consistent view of memory
Weak- and Strong Isolation

If guarantees are only given about memory accessed inside `atomic`, a TM implementation provides *weak isolation*. Can we mix transactions with code accessing memory non-transactionally?

- no conflict detection for non-transactional accesses
- standard *race* problems as in unlocked shared accesses

```c
// Thread 1
atomic {
    x = 42;
}
// Thread 2
int tmp = x;
```

⇝ give programs with races the same semantics as if using a single global lock for all `atomic` blocks

- *strong isolation* retains order between accesses to TM and non-TM

Definition (SLA)

The *single-lock atomicity* is a model in which the program executes as if all transactions acquire a single, program-wide mutual exclusion lock.

⇝ like *sequential consistency*, SLA is a statement about program equivalence
Disadvantages of the SLA model

The SLA model is *simple* but often too strong:

1. **SLA has a weaker *progress* guarantee than a transaction should have**
   ```
   // Thread 1
   atomic {
     while (true) {};
   }
   // Thread 2
   atomic {
     int tmp = x; // x in TM
   }
   
   ▶ under the SLA model, *atomic {}* acts as barrier
   ▶ intuitively, the two transactions should be independent rather than synchronize
   
   ⇝ need a weaker model for more flexible implementation of *strong isolation*
   ```

2. **SLA correctness is too strong in practice**
   ```
   // Thread 1
   atomic {
     data = 1;
   }
   atomic {
     ready = 1;
   }
   
   // Thread 2
   atomic {
     int tmp = data;
     if (ready) {
       // use tmp
     }
   }
   ```
How about a more permissive view of transaction semantics?

- TM should not have the blocking behaviour of locks
- the programmer cannot rely on synchronization

**Definition (TSC)**

The *transactional sequential consistency* is a model in which the accesses within each transaction are sequentially consistent.

- TSC is weaker: gives *strong isolation*, but allows parallel execution ✓
- TSC is stronger: accesses within a transaction may not be re-ordered !

一緞 actual implementations use TSC with some *race free* re-orderings
Software Transactional Memory
Translation of atomic-Blocks

A TM system must track which shared memory locations are accessed:
- convert every read access \( x \) from a shared variable to \( \text{ReadTx}(&x) \)
- convert every write access \( x = e \) to a shared variable to \( \text{WriteTx}(&x,e) \)

Convert atomic blocks as follows:

```
atomic {
    // code
}
```

\[ \Rightarrow \]

```
do {
    \text{StartTx}();
    // code with \text{ReadTx} and \text{WriteTx}
} \text{while} (!\text{CommitTx}());
```

- translation can be done using a pre-processor
  - determining a minimal set of memory accesses that need to be transactional
    requires a good static analysis
  - idea: translate all accesses to global variables and the heap as TM
  - more fine-grained control using manual translation

- an actual implementation might provide a \texttt{retry} keyword
  - when executing \texttt{retry}, the transaction aborts and re-starts
  - the transaction will again wind up at \texttt{retry} unless its \textit{read set} changes
  - block until a variable in the read-set has changed
  - similar to condition variables in monitors \( \checkmark \)
A Software TM Implementation

A software TM implementation allocates a *transaction descriptor* to store data specific to each *atomic* block, for instance:

- **undo-log** of writes if writes have to be undone if a commit fails
- **redo-log** of writes if writes are postponed until a commit
- **read-** and **write-set**: locations accessed so far
- **read-** and **write-version**: time stamp when value was accessed

Example:
Consider the TL2 STM (software transactional memory) implementation [1]:

- provides **opacity**: zombie transactions do not see inconsistent state
- uses **lazy versioning**: writes are stored in a *redo*-log and done on commit
- **validating conflict detection**: accessing a modified address aborts
**Principles of TL2**

The idea: obtain a version from the global version counter on starting the transaction, the *read-version*, and watch out for accesses to newer versions throughout the transaction.

- A read ReadTx from a field at offset of object obj aborts,
  - when the objects version is younger than the
  - when the object is locked at the moment of access
  or returns the read value and adds the accessed memory address to the *read-set*.

- WriteTx is simpler: add or update the location in the *redo-log*.

- CommitTx successively
  1. picks up locks for each written object
  2. increments the global version
  3. checks the read objects for being up to date
  before writing redo-log entries to memory while updating their version and releasing their locks
Properties of TL2

Opacity is guaranteed by aborting on a read accessing an inconsistent value:

- StartTx
- ReadTx
- WriteTx
- ReadTx
- CommitTx

Memory state seems to be consistent:

- Validate read set
- Increment global clock
- Write redo-log

Other observations:

- Read-only transactions just need to check that read versions are consistent (no need to increment the global clock)
- Writing values still requires locks
  - Deadlocks are still possible
  - Since other transactions can be aborted, one can preempt transactions that are deadlocked
  - Since lock accesses are generated, computing a lock order up-front might be possible
- There might be contention on the global clock
General Challenges when using STM

Executing atomic blocks by repeatedly trying to execute them non-atomically creates new problems:

- a transaction might unnecessarily be aborted
  - the granularity of what is locked might be too large
  - a TM implementation might impose restrictions:
    ```c
    // Thread 1
    atomic { // clock=12
        ...
    }
    // Thread 2
    atomic {
        WriteTx(&x, 0) = 42; // clock=13
    }
    int r = ReadTx(&x, 0);
    } // tx.RV==12 != clock

- lock-based commits can cause contention
  - organize cells that participate in a transaction in one object
  - compute a new object as result of a transaction
  - atomically replace a pointer to the old object with a pointer to the new object if the old object has not changed
    ⇝ idea of the original STM proposal

- TM system should figure out which memory locations must be logged

- danger of live-locks: transaction B might abort A which might abort B ...
Integrating Non-TM Resources

Allowing access to other resources than memory inside an atomic block poses problems:

- storage management, condition variables, volatile variables, input/output
- semantics should be as if atomic implements SLA or TSC semantics

Usual choice is one of the following:

- **Prohibit It.** Certain constructs do not make sense. Use compiler to reject these programs.
- **Execute It.** I/O operations may only happen in some runs (e.g. file writes usually go to a buffer). Abort if I/O happens.
- **Irrevocably Execute It.** Universal way to deal with operations that cannot be undone: enforce that this transaction terminates (possibly before starting) by making all other transactions conflict.
- **Integrate It.** Re-write code to be transactional: error logging, writing data to a file, . . . .

⇝ currently best to use TM only for memory; check if TM supports irrevocable transactions
Hardware Transactional Memory
Hardware Transactional Memory

Transactions of a limited size can also be implemented in hardware:
- additional hardware to track read- and write-sets
- conflict detection is *eager* using the cache:
  - additional hardware makes it cheap to perform conflict detection
  - if a cache-line in the read set is invalidated, the transaction aborts
  - if a cache-line in the write set must be written-back, the transaction aborts

⇝ limited by fixed hardware resources, a software backup must be provided

Two principal implementation of HTM:

1. **Explicit Transactional Memory**: each access is marked as transactional
   - similar to `StartTx`, `ReadTx`, `WriteTx`, and `CommitTx`
   - requires separate transaction instructions
   ⇝ a transaction has to be translated differently

! mixing transactional and non-transactional accesses is problematic

2. **Implicit Transactional Memory**: only the beginning and end of a transaction are marked
   - same instructions can be used, hardware interprets them as transactional
   - only instructions affecting memory that can be cached can be executed transactionally
   - hardware access, OS calls, page table changes, etc. all abort a transaction
   ⇝ provides *strong isolation*
Example for HTM

AMD Advanced Synchronization Facilities (ASF):
- defines a logical *speculative region*
- `LOCK MOV` instructions provide *explicit* data transfer between normal memory and speculative region
- aimed to implement larger atomic operations

Intel’s TSX in Broadwell/Skylake microarchitecture (since Aug 2014):
- *implicitly transactional*, can use normal instructions within transactions
- tracks read/write set using a single `transaction` bit on cache lines
- provides space for a backup of the whole CPU state (registers, ...)
- use a simple counter to support nested transactions
- may abort at any time due to lack of resources
- aborting in an inner transaction means aborting all of them

Intel provides two software interfaces to TM:
1. Restricted Transactional Memory (RTM)
2. Hardware Lock Elision (HLE)
Restricted Transactional Memory
Restricted Transactional Memory (Intel)

Provides new instructions **XBEGIN**, **XEND**, **XABORT**, and **XTEST**:

- **XBEGIN** takes an instruction address where execution continues if the transaction aborts
- **XEND** commits the transaction started by the last **XBEGIN**
- **XABORT** aborts the current transaction with an error code
- **XTEST** checks if the processor is executing transactionally

The instruction **XBEGIN** can be implemented as a C function:

```c
int data[100]; // shared

void update(int idx, int value) {
    if(_xbegin()==-1) {
        data[idx] += value;
        _xend();
    } else {
        // transaction failed
    }
}
```

⇝ user must provide fall-back code
Considerations for the Fall-Back Path

Consider executing the following code in parallel with itself:

```c
int data[100]; // shared
void update(int idx, int value) {
    if(_xbegin()==-1) {
        data[idx] += value;
        _xend();
    } else {
        data[idx] += value;
    }
}
```

⚠️ Problem:

- if the fall-back code is executed, it might be interrupted by the transaction
- the write in the fall-back path thereby overwrites the value of the transaction

⇒ need to ensure that the fall-back path is executed atomically
Protecting the Fall-Back Path

Use a lock to prevent the transaction from interrupting the fall-back path:

```c
int data[100]; // shared
int mutex;
void update(int idx, int value) {
    if(_xbegin()==-1) {
        if (!mutex>0) _xabort();
        data[idx] += value;
        _xend();
    } else {
        wait(mutex);
        data[idx] += value;
        signal(mutex);
    }
}
```

- fall-back path may not run in parallel with others ✓
- ⚠️ transactional region may not run in parallel with fall-back path
Implementing RTM using the Cache

Transactional operation:
- augment each cache line with an extra bit $T$
- use a nesting counter $C$ and a backup register set

additional transaction logic:
- **XBEGIN** increments $C$ and, if $C = 0$, back up registers
- read or write access to a cache line set $T$ if $C > 0$
- applying an *invalidate* message from *invalidate queue* to a cache line with $T$ flag issues **XABORT**
- observing a *read* for a *modified* cache line with $T$ flag issues **XABORT**
- **XABORT** clears all $T$ flags, invalidates the former $T$ lines, sets $C = 0$ and restores CPU registers
- **XCOMMIT** decrement $C$ and, if $C = 0$, clear all $T$ flags
Illustrating Transactions

Augment MESI states with extra bit $T$. CPU A: d:E5 t:E0, CPU B: d:I

Thread A

```c
int t = _xbegin();
int tmp = data[idx];
data[idx] = tmp+value;
_xend();
```

Thread B

```c
_xbegin();
int tmp = data[idx];
data[idx] = tmp+value;
_xend();
```
Common Code Pattern for Mutexes

Using HTM in order to implement mutex:

```c
int data[100]; // shared
int mutex;
void update(int idx, int val) {
  if(_xbegin()==-1) {
    if (!mutex>0) _xabort();
    data[idx] += val;
    _xend();
  } else {
    wait(mutex);
    data[idx] += val;
    signal(mutex);
  }
}
```

```c
void update(int idx, int val) {
  lock(&mutex);
  data[idx] += val;
  unlock(&mutex);
}
```

```c
void lock(int* mutex) {
  if(_xbegin()==-1) {
    if (!*mutex>0) _xabort();
    else return;
  } wait(mutex);
}
```

```c
void unlock(int* mutex) {
  if (!*mutex>0) signal(mutex);
  else _xend();
}
```

- critical section may be executed without taking the lock (the lock is *elided*)
- as soon as one thread conflicts, it aborts, takes the lock in the fallback path and thereby aborts all other transactions that have read mutex
Hardware Lock Elision
**Observation:** Using HTM to implement lock elision is a common pattern to provide special handling in hardware: HLE.

- Provides a way to execute a critical section without the need to immediately modify the cacheline in order to acquire and release the lock.
- Requires annotations:
  - Instruction that increments the semaphore must be prefixed with `XACQUIRE`.
  - Instruction setting the semaphore to 0 must be prefixed with `XRELEASE`.
  - These prefixes are ignored on older platforms.
- For a successful elision, all signal/wait operations of a lock must be annotated.
Implementing Lock Elision

Transactional operation:

- re-uses infrastructure for Restricted Transactional Memory
- add a buffer for elided locks, similar to store buffer

- **XACQUIRE** of lock ensures *shared/exclusive* cache line state with \( T = 1 \), issues **XBEGIN** and stores written value in *elided lock* buffer
- r/w access to a cache line sets \( T \)
- like RTM, applying an *invalidate* message to a cache line with \( T = 1 \) issues **XABORT**, analogous for *read* message to a *modified* cache line
- a *local CPU read* from the address of the elided lock accesses the buffer
- on **XRELEASE** on the same lock, decrement \( C \) and, if \( C = 0 \), clear \( T \) flags and elided locks buffer and commit to memory
Transactional Memory: Summary

Transactional memory aims to provide atomic blocks for general code:

- frees the user from deciding how to lock data structures
- compositional way of communicating concurrently
- can be implemented using software (locks, atomic updates) or hardware

It is hard to get the details right:

- semantics of explicit HTM and STM transactions quite subtle when mixing with non-TM (weak vs. strong isolation)
- single-lock atomicity vs. transactional sequential consistency semantics
- STM not the right tool to synchronize threads without shared variables
- TM providing opacity (serializability) requires eager conflict detection or lazy version management

Pitfalls in implicit HTM:

- RTM requires a fall-back path
- no progress guarantee
- HLE can be implemented in software using RTM
Availability of TM Implementations:

- GCC can translate accesses in `__transaction_atomic` regions into `libitm` library calls
- The library `libitm` provides different TM implementations:
  1. On systems with TSX, it maps atomic blocks to HTM instructions
  2. On systems without TSX and for the fallback path, it resorts to STM

RTM support slowly introduced to OpenJDK Hotspot monitors

Use of hardware lock elision is limited:

- Allows to easily convert existing locks
- `pthread` locks in `glibc` use RTM [https://lwn.net/Articles/534758/](https://lwn.net/Articles/534758/):
  - Allows implementation of back-off mechanisms
  - HLE only special case of general lock

Implementing monitors is challenging:

- Lock count and thread id may lead to conflicting accesses
- In `pthreads`: error conditions often not checked anymore
Outlook

Several other principles exist for concurrent programming:

1. **non-blocking message passing (the actor model)**
   - a program consists of actors that send messages
   - each actor has a queue of incoming messages
   - messages can be processed and new messages can be sent
   - special filtering of incoming messages
   - **example**: Erlang, many add-ons to existing languages

2. **blocking message passing (CSP, $\pi$-calculus, join-calculus)**
   - a process sends a message over a channel and blocks until the recipient accepts it
   - channels can be send over channels ($\pi$-calculus)
   - **examples**: Occam, Occam-$\pi$, Go

3. **(immediate) priority ceiling**
   - declare *processes* with priority and *resources* that each process may acquire
   - each resource has the maximum (ceiling) priority of all processes that may acquire it
   - a process’ priority at run-time increases to the maximum of the priorities of held resources
   - the process with the maximum (run-time) priority executes
References

D. Dice, O. Shalev, and N. Shavit.
Transactional Locking II.

T. Harris, J. Larus, and R. Rajwar.
Transactional memory, 2nd edition.

Online resources on Intel HTM and GCC’s STM:

   fun-with-intel-transactional-synchronization-extensions
