A Hybrid TM for Haskell

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Outline

- Haskell STM as it is now [Harris et al., 2005].
- Our work, extending Haskell STM into a hybrid TM.
- Haskell-specific challenges and opportunities.
- Future work, supporting more of Haskell TM in hardware transactions.
As of writing, around 280 open source libraries in the Haskell ecosystem depend on STM.

Reasons for using Haskell STM:

- It is easy!
- Expressive API with retry and orElse.
- Trivial to build into libraries.
But...

Poor performance.

- The default fine-grain locking scheme performs very poorly under contention.
- Around 7X performance overhead in the best conditions.
- Gets much worse as the number of transactional variables increases.
- Metadata granularity.
Haskell STM Example

transA = do
    v <- dequeue queue1
    return v

transB = do
    v <- dequeue queue2
    if someCondition v
        then return v
        else retry

mainLoop = do
    a <- atomically $ transA ‘orElse‘ transB ‘orElse‘ ...
    handleRequest a
mainLoop
Opportunity

Haskell’s TM already encourages the use of only a few transactional variables and transactions that are focused on performing a minimal amount of work.

This sounds like a good fit for hardware transactions!
Transactional Synchronization Extensions (TSX)

- **Hardware Lock Elision (HLE)**
  - XACQUIRE and XRELEASE prefixes for lock operations.

- **Restricted Transactional Memory (RTM)**
  - XBEGIN marks beginning of a transaction.
  - XTEST determines if execution is in a transaction.
  - XABORT aborts a transaction and returns an 8-bit reason code.
  - XEND ends a transaction.
Limitations (4th generation core architecture)

- Cache line granularity.
- Some instructions are not allowed in a transaction.
- Writes limited by L1 data cache capacity and associativity.
- Reads do not appear to have this limitation.
- No guarantee that any particular transaction will complete.
Glasgow Haskell Compiler (GHC), 7.6.3
- Explicit transactional variables.
- Lazy value-based validation.
- Object based.
Haskell STM Implementation

Coarse-grain Lock

- Serialize commits with a global lock
- Similar to NOrec [Dalessandro et al., 2010, Dalessandro et al., 2011, Riegel et al., 2011].

Fine-grain Locks

- Lock for each TVar.
- Two-phase commit.
- Similar to object-based STM [Fraser, 2004].
Haskell STM Metadata Structure

- **Node**
  - key
  - value
  - parent
  - left
  - right
  - color

- **TVar**
  - value
  - watch

- **Watch Queue**
  - thread
  - next
  - prev

- **Watch Queue**
  - thread
  - next
  - prev

- **TRec**
  - prev
  - index
  - tvar
  - old
  - new
  - ...
Haskell Hybrid TM (Our Work)

- Three levels for transactions [Matveev and Shavit, 2013].
  - Full transactions in hardware.
  - Software transaction, commit in hardware.
  - Full software fallback.
In full hardware transaction we can safely read the global lock just before commit (XEND).

- Haskell’s limited and explicit effects make this safe.
- If a partial software commit is seen in a hardware transaction, the worst behavior it can do is an infinite loop. This will be terminated by GC or context switch.
Implementation Roadblocks

- C ABI vs Cmm ABI
- Indirection overhead

An expected issue for the future

- Lazy evaluation’s memoization.
Reads from a red-black tree. At each size tree, each of 4 threads performs 5,000 transactions of 40 lookups each.
Preliminary Results (Intel® Core™ i7-4770, 3.4GHz)

![Graph showing the total time (seconds) vs. red-black tree size for different methods: STM-Fine, Hybrid, STM-Coarse, and HLE.

 Writes to a red-black tree. At each size tree, 4 threads together eventually replace every node in the tree 10 times, by atomically deleting one node and inserting another.
Existing retry Implementation

- When retry is encountered, add the thread to the watch list of each TVar in the transaction’s TRec.
- When a transaction commits, wake up all transactions in watch lists on TVars it writes.
Future Implementation Work (retry)

Supporting retry in Hardware Transactions

- Throw away the writes and record the read set.
- XABORT only gives us 8-bits. If we had a non-transactional write we could get more.
  - Sacrifice wakeup accuracy with a constant space approximation of the read-set.
  - Use the 8-bits as a degenerative Bloom filter.
Atomic choice between transactions biased toward the first.

- Nested TRecs allow for partial rollback.
- If the first transaction encounters retry, throw away the writes, but merge the reads and move to the second transaction.
Future Implementation Work (orElse)

Supporting orElse in Hardware Transactions

- No direct support in hardware for a partial rollback.
- If the first transaction does not write to any TVars, there is nothing to roll back.
  - Keep a TRec while running the first transaction.
  - Or rewrite the first transaction to delay writes until after the choice to retry.
Summary

- Performance improvements when using HTM.
- Challenges
  - Indirection
  - Calling convention overhead
- Lazy late lock subscription feasible in Haskell.
- False sharing problem induced by lazy evaluation’s memoization.
- Plan for handling retry and orElse in HTM.
Haskell STM TQueue Implementation

```haskell
data TQueue a = TQueue (TVar [a]) (TVar [a])

dequeue :: TQueue a -> a -> STM ()
dequeue (TQueue _ write) v = modifyTVar write (v:)

enqueue :: TQueue a -> STM a
enqueue (TQueue read write) =
  readTVar read >>= \case
    (v:vs) -> writeTVar read vs >>= return v
    [] -> reverse <$> readTVar write >>= \case
      [] -> retry
      (v:vs) -> do writeTVar write []
                  writeTVar read vs
                  return v
```
Haskell STM Implementation

Fairly standard commit protocol, but missing optimizations from more recent work.

<table>
<thead>
<tr>
<th>Commit</th>
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<tbody>
<tr>
<td>- Coarse grain: perform writes while holding the global lock.</td>
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<tr>
<td>- Fine grain:</td>
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<tr>
<td>- Acquire locks for writes while validating.</td>
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<tr>
<td>- Check that read-only variables are still valid while holding the write locks.</td>
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<tr>
<td>- Perform writes and release locks.</td>
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Broken code that we are not allowed to write!

```haskell
transferBad :: TVar Int -> TVar Int -> Int -> STM ()
transferBad accountX accountY value = do
  x <- readTVar accountX
  y <- readTVar accountY

  writeTVar accountX (x + v)
  writeTVar accountY (y - v)

  if x < 0
    then launchMissles
    else return ()
```
Broken code that we are not allowed to write!

```haskell
thread :: IO ()
thread = do
    transfer a b 200
    transfer a c 300
```
C ABI vs Cmm ABI

- GHC’s runtime support for STM is written in C.
- Code is generated in Cmm and calls into the runtime are essentially foreign calls with significant extra overhead.
- We avoid this by writing the HTM support in Cmm.
- Typeclass machinery could allow deeper code specialization.
Lazy evaluation may lead to false conflicts due to the update step that writes back the fully evaluated value.

One solution could be to delay performing updates (to shared values) until after a transaction commits.

Races here are fine as any update must represent the same value.
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