NON-BLOCKING DATA STRUCTURES
AND TRANSACTIONAL MEMORY

Tim Harris, 17 Oct 2018
Lecture 3/3

- Problems with locks
- Atomic blocks and composition
- Hardware transactional memory
- Software transactional memory
Transactional Memory

Companion slides for
The Art of Multiprocessor Programming
by Maurice Herlihy & Nir Shavit
Our Vision for the Future

In this course, we covered …

Best practices …

New and clever ideas …

And common-sense observations.
Our Vision for the Future

In this course, we covered ....

Nevertheless ...

Concurrent programming is still too hard ...

Here we explore why this is ....

And what we can do about it.
Locking
Coarse-Grained Locking

Easily made correct …  
But not scalable.
Fine-Grained Locking

Can be tricky …
Locks are not Robust

If a thread holding a lock is delayed …

No one else can make progress
Locking Relies on Conventions

• Relation between
  – Locks and objects
  – Exists only in programmer’s

/*
 * When a locked buffer is visible to the I/O layer
 * BH_Launder is set. This means before unlocking
 * we must clear BH_Launder, mb() on alpha and then
 * clear BH_Lock, so no reader can see BH_Launder set
 * on an unlocked buffer and then risk to deadlock.
 */
Simple Problems are hard

Double-ended queue

$\text{enq}(x)$

No interference if ends “far apart”

$\text{enq}(y)$

Interference OK if queue is small

Clean solution is publishable result:
[Michael & Scott PODC 97]
Locks Not Composable

Transfer item from one queue to another

Must be atomic:
No duplicate or missing items
Locks Not Composable

- Lock source
- Unlock source & target
- Lock target
Locks Not Composable

Methods cannot provide internal synchronization.

Objects must expose locking protocols to clients.

Clients must devise and follow protocols.

Abstraction broken!
Monitor Wait and Signal

If buffer is empty, wait for item to show up.

Yes!

Empty buffer
Wait and Signal do not Compose

Wait for either?
The Transactional Manifesto

- Current practice inadequate
  - to meet the multicore challenge
- Research Agenda
  - Replace locking with a transactional API
  - Design languages or libraries
  - Implement efficient run-time systems
Transactions

Block of code ....

Atomic: appears to happen instantaneously

Serializable: all appear to happen in one-at-a-time

Commit: takes effect (atomically)

Abort: has no effect (typically restarted)
Atomic Blocks

```java
atomic {
    x.remove(3);
    y.add(3);
}

atomic {
    y = null;
}
```
Atomic Blocks

```java
atomic {
    x.remove(3);
    y.add(3);
}
```

```java
atomic {
    y = null;
}
```

No data race
A Double-Ended Queue

```java
public void LeftEnq(item x) {
    Qnode q = new Qnode(x);
    q.left = left;
    left.right = q;
    left = q;
}
```

Write sequential Code
public void LeftEnq(item x) {
    atomic {
        Qnode q = new Qnode(x);
        q.left = left;
        left.right = q;
        left = q;
    }
}
A Double-Ended Queue

public void LeftEnq(item x) {
    atomic {
        Qnode q = new Qnode(x);
        q.left = left;
        left.right = q;
        left = q;
    }
}

Enclose in atomic block
Warning

• Not always this simple
  – Conditional waits
  – Enhanced concurrency
  – Complex patterns

• But often it is…
Composition?
Composition?

```java
public void Transfer(Queue<T> q1, q2) {
    atomic {
        T x = q1.deq();
        q2.enq(x);
    }
}
```

Trivial or what?
public T LeftDeq() {
    atomic {
        if (left == null)
            retry;
        ...
    }
}
Composable Conditional Waiting

```java
atomic {
    x = q1.deq();
} orElse {
    x = q2.deq();
}
```

Run 1\textsuperscript{st} method. If it retries …

Run 2\textsuperscript{nd} method. If it retries …

Entire statement retries
Hardware Transactional Memory

- Exploit Cache coherence
- Already almost does it
  - Invalidation
  - Consistency checking
- Speculative execution
  - Branch prediction = optimistic synch!
HW Transactional Memory

read

active

Interconnect

caches

memory
Transactional Memory

active

read

t
active
caches

memory

Art of Multiprocessor Programming
Transactional Memory

- Committed
- Active
- Caches
- Memory
Transactional Memory

committed

active

caches

memory

write
Transaction Commit

• At commit point
  – If no cache conflicts, we win.

• Mark transactional entries
  – Read-only: valid
  – Modified: dirty (eventually written back)

• That’s all, folks!
  – Except for a few details ...
Not all Skittles and Beer

• Limits to
  – Transactional cache size
  – Scheduling quantum

• Transaction cannot commit if it is
  – Too big
  – Too slow
  – Actual limits platform-dependent
HTM Strengths & Weaknesses

• Ideal for lock-free data structures
HTM Strengths & Weaknesses

• Ideal for lock-free data structures

• Practical proposals have limits on
  – Transaction size and length
  – Bounded HW resources
  – Guarantees vs best-effort
HTM Strengths & Weaknesses

• Ideal for lock-free data structures
• Practical proposals have limits on
  – Transaction size and length
  – Bounded HW resources
  – Guarantees vs best-effort
• On fail
  – Diagnostics essential
  – Try again in software?
Locks don’t compose, transactions do.

Composition necessary for Software Engineering.

But practical HTM doesn’t really support composition!

Why we need STM
Transactional Consistency

- Memory Transactions are collections of reads and writes executed atomically.
- They should maintain consistency
  - *External*: with respect to the interleavings of other transactions (*linearizability*).
  - *Internal*: the transaction itself should operate on a consistent state.
External Consistency

Invariant \( x = 2y \)

Transaction A:
- Write \( x \)
- Write \( y \)

Transaction B:
- Read \( x \)
- Read \( y \)

Compute \( z = \frac{1}{(x-y)} = \frac{1}{2} \)
A Simple Lock-Based STM

- STMs come in different forms
  - Lock-based
  - Lock-free
- Here: a simple lock-based STM
- Let's start by Guaranteeing External Consistency
Synchronization

• Transaction keeps
  – **Read set**: locations & values read
  – **Write set**: locations & values to be written

• Deferred update
  – Changes installed at commit

• Lazy conflict detection
  – Conflicts detected at commit
STM: Transactional Locking

Application Memory

Map

Array of version #s & locks
Reading an Object

Add version numbers & values to read set
To Write an Object

Add version numbers & new values to **write set**
To Commit

Mem

Locks

- Acquire write locks
- Check version numbers unchanged
- Install new values
- Increment version numbers
- Unlock.
1. To Read: load lock + location
2. Check unlocked add to Read-Set
3. To Write: lock location, store value
4. Add old value to undo-set
5. Validate read-set v#’s unchanged
6. Release each lock with v#+1

Quick read of values freshly written by the reading transaction
Commit Time Locking (Write Buff)

1. To Read: load lock + location
2. Location in write-set? (Bloom Filter)
3. Check unlocked add to Read-Set
4. To Write: add value to write set
5. Acquire Locks
6. Validate read/write v#’s unchanged
7. Release each lock with v#+1

Hold locks for very short duration
COM vs. ENC High Load

Red-Black Tree 20% Delete 20% Update 60% Lookup

Hand
COM
ENC
MCS
COM vs. ENC Low Load

Red-Black Tree 5% Delete 5% Update 90% Lookup

Graph showing performance comparison between COM and ENC under low load conditions.
Problem: Internal Inconsistency

- A Zombie is an active transaction destined to abort.
- If Zombies see inconsistent states bad things can happen
Internal Consistency

Invariant: \( x = 2y \)

Transaction A: reads \( x = 4 \)

Transaction B: writes 8 to \( x \), 16 to \( y \), aborts A

Transaction A: (zombie)
reads \( y = 4 \)
computes \( 1/(x-y) \)

Divide by zero FAIL!
Solution: The Global Clock (The TL2 Algorithm)

- Have one shared global clock
- Incremented by (small subset of) writing transactions
- Read by all transactions
- Used to validate that state worked on is always consistent
Read-Only Transactions

Copy version clock to local read version clock
Read-Only Transactions

Mem

Locks

Copy version clock to local read version clock

Read lock, version #, and memory

Shared Version Clock

Private Read Version (RV)
Read-Only Transactions

Mem

Locks

12

32

56

19

17

Copy version clock to local

Read lock, version #, and
memory, check version #s less than

On Commit:
check unlocked &
version #s less than
local read clock

Shared Version Clock

Private Read Version (RV)
Read-Only Transactions

We have taken a snapshot without keeping an explicit read set!
Example Execution: Read Only Trans

1. \( \text{RV} \leftarrow \text{Shared Version Clock} \)
2. On Read: read lock, read mem, read lock: check unlocked, unchanged, and \( v\# \leq \text{RV} \)
3. Commit.

Reads form a snapshot of memory.
No read set!
Ordinary (Writing) Transactions

Mem | Locks
--- | ---
12 |  
32 |  
56 |  
19 |  
17 |  

- Copy version clock to local read version clock
- Shared Version Clock
- Private Read Version (RV)
Ordinary Transactions

Mem

<table>
<thead>
<tr>
<th>Mem</th>
<th>Locks</th>
</tr>
</thead>
<tbody>
<tr>
<td>12</td>
<td></td>
</tr>
<tr>
<td>32</td>
<td></td>
</tr>
<tr>
<td>56</td>
<td></td>
</tr>
<tr>
<td>19</td>
<td></td>
</tr>
<tr>
<td>17</td>
<td></td>
</tr>
</tbody>
</table>

Copy version clock to local read version clock

On read/write, check:
Unlocked & version # < RV
Add to R/W set

Shared Version Clock

Private Read Version (RV)
On Commit

Mem

|   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |
|12 |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |
|32 |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |
|56 |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |
|19 |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |
|17 |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |

- Acquire write locks
- Shared Version Clock
- Private Read Version (RV)

Art of Multiprocessor Programming
On Commit

- Acquire write locks
- Increment Version Clock

Shared Version Clock: 101
Private Read Version (RV): 100
On Commit

Mem

Locks

Acquire write locks
Increment Version Clock
Check version numbers ≤ RV

12
32
56
19
17

101
100

Shared Version Clock
Private Read Version (RV)
On Commit

Mem

Acquire write locks
Increment Version Clock
Check version numbers < RV
Update memory

Shared Version Clock
Private Read Version (RV)
On Commit

Mem

Locks

Acquire write locks
Increment Version Clock
Check version numbers < RV
Update memory
Update write version #s

101
101
100
101
101
12
101
56
19

Shared Version Clock
Private Read Version (RV)
Example: Writing Trans

1. \( RV \leftarrow \) Shared Version Clock
2. On Read/Write: check unlocked and \( v\# \leq RV \) then add to Read/Write-Set
3. Acquire Locks
4. \( WV = F&I(VClock) \)
5. Validate each \( v\# \leq RV \)
6. Release locks with \( v\# \leftarrow WV \)

Reads+Inc+Writes = serializable
TM Design Issues

- Implementation choices
- Language design issues
- Semantic issues
Granularity

• Object
  – managed languages, Java, C#, …
  – Easy to control interactions between transactional & non-trans threads

• Word
  – C, C++, …
  – Hard to control interactions between transactional & non-trans threads
Direct/Deferred Update

• **Deferred**
  – modify private copies & install on commit
  – Commit requires work
  – Consistency easier

• **Direct**
  – Modify in place, roll back on abort
  – Makes commit efficient
  – Consistency harder
Conflict Detection

• **Eager**
  – Detect before conflict arises
  – “Contention manager” module resolves
• **Lazy**
  – Detect on commit/abort
• **Mixed**
  – Eager write/write, lazy read/write …
Conflict Detection

- Eager detection may abort transactions that could have committed.
- Lazy detection discards more computation.
Contention Management & Scheduling

• How to resolve conflicts?
• Who moves forward and who rolls back?
• Lots of empirical work but formal work in infancy
Contestation Manager Strategies

• Exponential backoff
• Priority to
  – Oldest?
  – Most work?
  – Non-waiting?
• None Dominates
• But needed anyway

Judgment of Solomon
I/O & System Calls?

• Some I/O revocable
  – Provide transaction-safe libraries
  – Undoable file system/DB calls

• Some not
  – Opening cash drawer
  – Firing missile
I/O & System Calls

• One solution: make transaction irrevocable
  – If transaction tries I/O, switch to irrevocable mode.

• There can be only one ...
  – Requires serial execution

• No explicit aborts
  – In irrevocable transactions
Exceptions

```java
int i = 0;
try {
    atomic {
        i++;
        node = new Node();
    }
} catch (Exception e) {
    print(i);
}
```
Exceptions

Throws OutOfMemoryException!

```java
int i = 0;
try {
    atomic {
        i++;
        node = new Node();
    }
} catch (Exception e) {
    print(i);
}
```
int i = 0;
try {
    atomic {
        i++;
        node = new Node();
    }
} catch (Exception e) {
    print(i);
}
Unhandled Exceptions

- Aborts transaction
  - Preserves invariants
  - Safer
- Commits transaction
  - Like locking semantics
  - What if exception object refers to values modified in transaction?
Nested Transactions

```c
atomic void foo() {
    bar();
}

atomic void bar() {
    ...
}
```
Nested Transactions

• Needed for modularity
  – Who knew that \texttt{cosine()} contained a transaction?

• Flat nesting
  – If child aborts, so does parent

• First-class nesting
  – If child aborts, partial rollback of child only
Hatin’ on TM

STM is too inefficient
Hatin’ on TM

Requires radical change in programming style
Hatin’ on TM

Erlang-style shared nothing only true path to salvation
There is nothing wrong with what we do today.
Gartner Hype Cycle

- Technology Trigger
- Peak of Inflated Expectations
- Plateau of Productivity
- Slope of Enlightenment
- Trough of Disillusionment

You are here

Hat tip: Jeremy Kemp
Thanks!

תודה
Overview

- Building shared memory data structures
  - Lists, queues, hashtables, ...

- Why?
  - Used directly by applications (e.g., in C/C++, Java, C#, ...)  
  - Used in the language runtime system (e.g., management of work, implementations of message passing, ...)  
  - Used in traditional operating systems (e.g., synchronization between top/bottom-half code)

- Why not?
  - Don’t think of “threads + shared data structures” as a default/good/complete/desirable programming model  
  - It’s better to have shared memory and not need it...
Different techniques for different problems

- Ease to write
- Correctness
- When can it be used?
- How fast is it?
- How well does it scale?