

CS 636: Transactional Memory

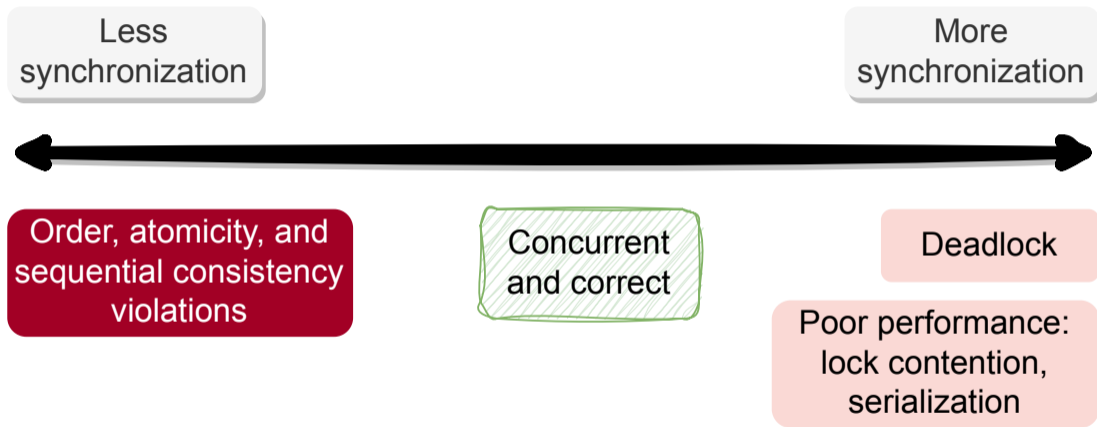
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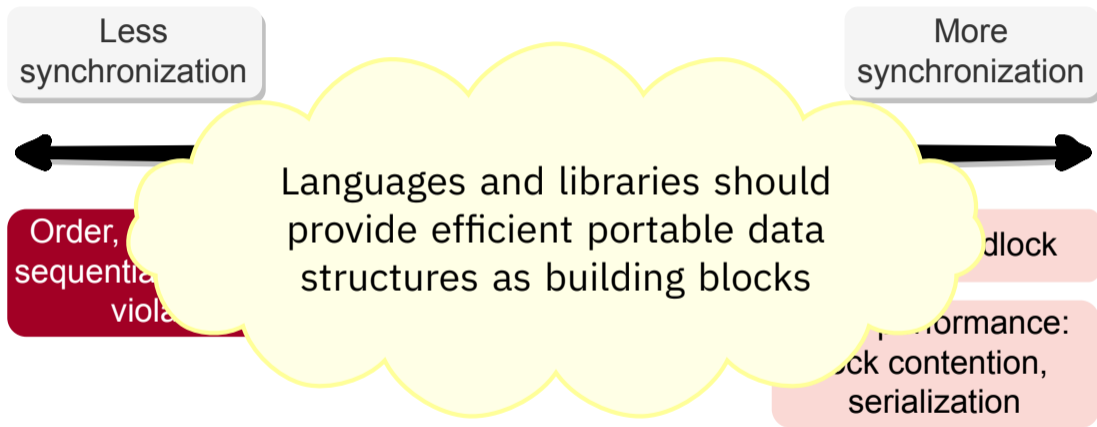
Sem 2024-25-II



Challenges with Concurrent Programming

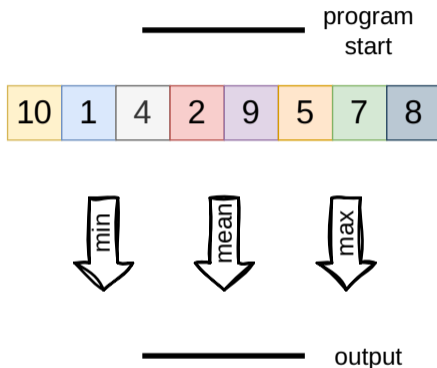


Challenges with Concurrent Programming



Task Parallelism

- Different tasks run on the same data
 - ▶ Threads execute computation concurrently (e.g., pipelines)
- Explicit synchronization is used to coordinate threads



HashMap in Java

```
1 public Object get(Object key) {  
2     int idx = hash(key); // Compute hash to find bucket  
3     HashEntry e = buckets[idx];  
4     while (e != null) { // Find element in bucket  
5         if (equals(key, e.key))  
6             return e.value;  
7         e = e.next;  
8     }  
9     return null;  
10 }
```

No lock overhead but
thread-unsafe

Synchronized HashMap in Java

```
1 public Object get(Object key) {  
2     synchronized (mutex) { // mutex guards all accesses  
3         return myHashMap.get(key);  
4     }  
5 }
```

Thread-safe but uses explicit
coarse-grained locking

Coarse-Grained and Fine-Grained Locking

Coarse-Grained Locking

- + Easy to implement correctly
- Limits concurrency, poor scalability

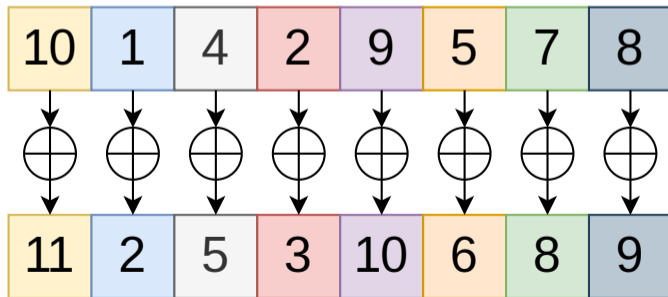
Fine-Grained Locking

- + More concurrency, better performance
- Difficult to get correct, more error-prone

Data Parallelism

Same task is applied on many data items in parallel

- E.g., processing pixels in an image
- Useful for numeric computations
- Not a universal programming model



Task vs Data Parallelism

Task Parallelism

- Different operations on same or different data
- Parallelization depends on task decomposition
- Speedup is usually less because of limited opportunities and synchronization

Data Parallelism

- Same operation on different data
- Parallelization proportional to the input data size
- Speedup is usually more

Abstraction and Composability

Programming models provide abstraction and composition

- For example, procedures, ADTs, and libraries
- Abstraction is a simplified view of an entity or a problem (e.g., procedures and ADT)
- Composability joins smaller units to form larger, more complex units (e.g., library methods)

Abstraction and Composability

Programming models provide abstraction and composition

- For example, procedures, ADTs, and libraries
- Abstraction is a simplified view of an entity or a problem (e.g., procedures and ADT)
- Composability joins smaller units to form larger, more complex units (e.g., library methods)

Parallel programming lacks abstraction mechanisms

- Low-level parallel programming models, such as threads and explicit synchronization, are unsuitable for constructing abstractions
- Explicit synchronization is not composable

Locks are difficult to program

- If a thread holding a lock is delayed, other contending threads cannot make progress
 - ▶ All contending threads will possibly wake up, but only one can make progress
- Lost wakeup — missed notify for condition variable
- Deadlock
- Priority inversion
- Lock convoying
- Locking relies on programmer conventions

Locks are difficult to program

- If a thread holding a lock is delayed, other contending threads cannot make progress
 - ▶ All contending threads will possibly wake up, but only one can make progress
- Lost wakeup — missed notify for condition variable
- Deadlock
- Priority inversion
- Lock convoying
- Lock

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

Lock-based Synchronization is not Composable

```
1 class HashTable {  
2     void synchronized insert(T elem);  
3     boolean synchronized remove(T elem);  
4 }
```

You may now want to add a new method move

```
1 boolean move(HashTable tab1, HashTable tab2, T elem)  
2     ⇒ remove()  
3     ⇒ insert()
```

Lock-based Synchronization is not Composable

```
1 class HashTable {  
2     void synchronized insert(T elem);  
3     boolean synchronized remove(T elem);  
4 }
```

Option: Add new methods such as LockHashTable() and
You may UnlockHashTable()

- 1 — Breaks the abstraction by exposing an implementation detail
- 2 — Lock methods are error prone
- 3 ▶ A client that locks more than one table must be careful to lock them
in a globally consistent order to prevent deadlock

Choosing the right locks!

- Locking schemes for 4 threads may not be the most efficient at 64 threads
- Need to profile the amount of contention

What about hardware atomic primitives?

Transactional Memory

Transactional Memory

- Transaction** A computation sequence that executes as if without external interference
- Computation sequence appears indivisible and instantaneous
 - Proposed by Lomet ['77] and Herlihy and Moss ['93]

Advantages of Transactional Memory (TM)

- + Provides reasonable tradeoff between abstraction and performance
- + No need for explicit locking
 - ▶ Avoids lock-related issues like lock convoying, priority inversion, and deadlock

```
1 boolean move(HashTable tab1, HashTable tab2, T elem) {  
2   atomic {  
3     boolean res = tab1.remove(elem);  
4     if (res)  
5       tab2.insert(elem);  
6   }  
7   return res;  
8 }
```

Advantages of TM

Programmer says what needs to be atomic

TM system/runtime implements synchronization

Declarative abstraction

- Programmer says what work should be done
- Programmer has to say how work should be done with imperative abstraction

Easy programmability (like coarse-grained locks)

Performance goal is like fine-grained locks

Basic TM Design

- Transactions are executed speculatively
- If the transaction execution completes without a conflict, then the transaction commits
 - ▶ The updates are made permanent
- If the transaction experiences a conflict, then it aborts

Database Systems as a Motivation

- Database systems have successfully exploited parallel hardware for decades
- Achieve good performance by executing many queries simultaneously and by running queries on multiple processors when possible

ACID properties

- Atomicity
- Consistency
- Isolation
- Durability

TM vs Database Transactions

TM

- Supported by language runtime or hardware
- Not durable
- Operations are from main memory, performance is critical

Databases

- Application level concept
- Durable
- Operations involve mostly disk accesses

Properties of TM execution

Atomic Appears to happen instantaneously

Commit Appears atomic

Abort Has no side effects

Serializable Appears to happen serially in order

Isolation Other transactions cannot observe writes before commit

TM Execution Semantics

Thread 1

```
1 atomic {  
2   a = a - 20;  
3   b = b + 20;  
4   c = a + b;  
5   a = a - b;  
6 }
```

Thread 2

```
1 atomic {  
2   c = c + 40;  
3   d = a + b + c;  
4 }  
5  
6
```

TM Execution Semantics

Thread 1

```
1 atomic {  
2   a = a - 20;  
3   b = b + 20;  
4   c = a + b;  
5   a = a - b;  
6 }
```

Thread 1's updates to a, b, and c are atomic

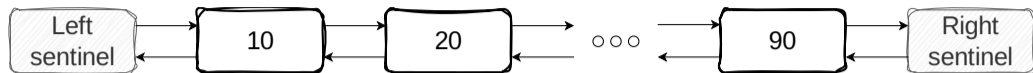
Thread 2

```
1 atomic {  
2   c = c + 40;  
3   d = a + b + c;  
4 }  
5
```

Thread 2 either sees ALL updates to a, b, and c from T1 or NONE

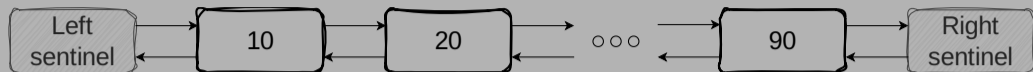
No data race due to TM semantics

Linked-List-based Double Ended Queue



```
1 void PushLeft(DQueue *q, int val) {  
2     QNode *qn = malloc(sizeof(QNode));  
3     qn->val = val;  
4     atomic {  
5         QNode *leftSentinel = q->left;  
6         QNode *oldLeftNode = leftSentinel->right;  
7         qn->left = leftSentinel;  
8         qn->right = oldLeftNode;  
9         leftSentinel->right = qn;  
10        oldLeftNode->left = qn;  
11    }  
12 }
```

Linked-List-based Double Ended Queue



```
1 void PushLeft(DQueue *q, int val) {  
2     QNode *qn = malloc(sizeof(QNode));  
3     qn->val = val;  
4     atomic {
```

Challenges with a lock-based implementation

- A single lock would prevent concurrent operations at both ends
- Need to be careful to avoid deadlocks with multiple locks
- Take care of corner cases (for example, only one element is left)

```
10     oldLeftNode->left = qn;  
11 }  
12 }
```

Atomicity Violations

Thread 1

```
1 ...
2 if (thd->proc_info) {
3
4
5     puts(thd->proc_info, ...)
6 }
7
8 ...
```

Thread 2

```
1
2 ...
3
4 thd->proc_info = NULL;
5
6 ...
7
8
```

MySQL: ha_innodb.cc

Fixing Atomicity Violations with TM

Thread 1

```
1 ...
2 atomic {
3     if (thd->proc_info) {
4         puts(thd->proc_info, ...)
5     }
6 }
```

Thread 2

```
1 ...
2 ...
3 ...
4 ...
5 ...
6 ...
7 atomic {
8     thd->proc_info = NULL;
9 }
10 ...
```

Fixing Atomicity Violations with TM

Thread 1

```
1  
2  
3  
4 ...  
5 atomic {  
6     if (thd->proc_info) {  
7         puts(thd->proc_info, ...)  
8     }  
9 }  
10 ...
```

Thread 2

```
1 ...  
2 atomic {  
3     thd->proc_info = NULL;  
4 }  
5 ...  
6  
7  
8  
9  
10
```

TM vs synchronized in Java

TM

- A transaction is atomic w.r.t. all other transactions in the system
- Nested transactions never deadlock

synchronized

- Provides mutual exclusion compared to other blocks on the same lock
- Nested blocks can deadlock if locks are acquired in wrong order

TM Interface

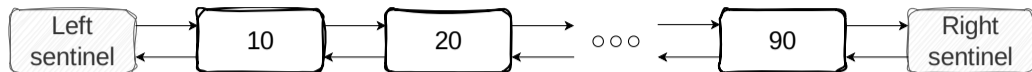
```
1 void startTx();
2 bool commitTx();
3 void abortTx();
4 T readTx(T *addr);
5 void writeTx(T *addr, T val);
```

Read set Set of variables read by the Tx

Write set Set of variables written by the Tx

Functions can be overloaded by types or we can use generics

Linked-List-based Double Ended Queue



```
1 void PushLeft(DQueue *q, int val) {  
2   QNode *qn = malloc(sizeof(QNode));  
3   qn->val = val;  
4   do {  
5     StartTx();  
6     QNode *leftSentinel = ReadTx(&(q->left));  
7     QNode *oldLeftNode = ReadTx(&(leftSentinel->right));  
8     WriteTx(&(qn->left), leftSentinel);  
9     WriteTx(&(qn->right), oldLeftNode);  
10    WriteTx(&(leftSentinel->right), qn);  
11    WriteTx(&(oldLeftNode->left), qn);  
12  } while(!commitTx());  
13 }
```

- Similar to sequential code
- No explicit locks

Transactions cannot replace all uses of locks

Thread 1

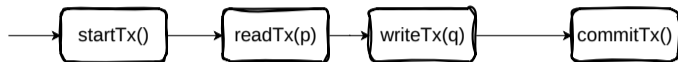
```
1 do {  
2   startTx();  
3   writeTx(&x, 1);  
4 } while (!commitTx());  
5
```

Thread 2

```
1 do {  
2   startTx();  
3   int tmp = readTx(&x);  
4   while (tmp == 0) {}  
5 } while (!commitTx());
```

Concurrency in TM

Thread 1

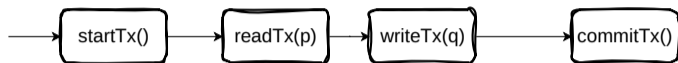


Thread 2

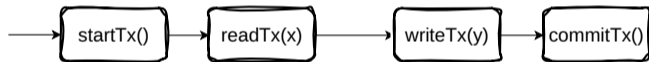


Concurrency in TM

Thread 1



Thread 2



Two levels

- (i) Among Tx's from concurrent thread
- (ii) Among individual Tx operations

Design Choices

Concurrency Control, Version Management, and Conflict Detection

TM Terminology

- A conflict occurs when two transactions perform conflicting operations on the same memory location
 - ▶ Let R_i and W_j be the read and write sets of Txs i and j . Then, a conflict occurs iff
 - ▶ $R_i \cap W_j \neq \emptyset$, or
 - ▶ $R_j \cap W_i \neq \emptyset$, or
 - ▶ $W_i \cap W_j \neq \emptyset$,
- The conflict is detected when the underlying TM system determines that the conflict has occurred
- The conflict is resolved when the underlying TM system takes some action to avoid the conflict
 - ▶ For example, delay or abort one of the conflicting transactions
- A conflict, its detection, and its resolution can occur at different times

TM Example Execution

bal = 1000;

Thread 1

```
1 atomic {  
2   tmp = bal;  
3   bal = tmp + 100;  
4 }
```

Location	Value read	Value written
----------	------------	---------------

Thread 2

```
1 atomic {  
2   tmp = bal;  
3   bal = tmp - 100;  
4 }
```

Location	Value read	Value written
----------	------------	---------------

TM Example Execution

bal = 1000;

Thread 1

```
1 atomic {  
2   tmp = bal;  
3   bal = tmp + 100;  
4 }
```

Location	Value read	Value written
----------	------------	---------------

Thread 2

```
1 atomic {  
2   tmp = bal;  
3   bal = tmp - 100;  
4 }
```

Location	Value read	Value written
----------	------------	---------------

bal	1000	
-----	------	--

TM Example Execution

bal = 1000;

Thread 1

```
1 atomic {  
2   tmp = bal;  
3   bal = tmp + 100;  
4 }
```

Location	Value read	Value written
----------	------------	---------------

bal	1000	
-----	------	--

Thread 2

```
1 atomic {  
2   tmp = bal;  
3   bal = tmp - 100;  
4 }
```

Location	Value read	Value written
----------	------------	---------------

bal	1000	
-----	------	--

TM Example Execution

bal = 1000;

Thread 1

```
1 atomic {  
2   tmp = bal;  
3   bal = tmp + 100;  
4 }
```

Location	Value read	Value written
----------	------------	---------------

bal	1000	1100
-----	------	------

Thread 2

```
1 atomic {  
2   tmp = bal;  
3   bal = tmp - 100;  
4 }
```

Location	Value read	Value written
----------	------------	---------------

bal	1000	
-----	------	--

TM Example Execution

bal = 1100;

Thread 1

```
1 atomic {  
2   tmp = bal;  
3   bal = tmp + 100;  
4 }
```

Location	Value read	Value written
----------	------------	---------------

bal	1000 ✓	1100
-----	--------	------

Thread 1's Tx ends, updates are committed, value of bal is written to memory, Tx log is discarded

Thread 2

```
1 atomic {  
2   tmp = bal;  
3   bal = tmp - 100;  
4 }
```

Location	Value read	Value written
----------	------------	---------------

bal	1000	
-----	------	--

TM Example Execution

bal = 1100;

Thread 1

```
1 atomic {  
2   tmp = bal;  
3   bal = tmp + 100;  
4 }
```

Thread 2

```
1 atomic {  
2   tmp = bal;  
3   bal = tmp - 100;  
4 }
```

Location	Value read	Value written
bal	1000	900

TM Example Execution

bal = 1100;

Thread 1

```
1 atomic {  
2   tmp = bal;  
3   bal = tmp + 100;  
4 }
```

Thread 2

```
1 atomic {  
2   tmp = bal;  
3   bal = tmp - 100;  
4 }
```

Location	Value read	Value written
bal	1000 X	900

Thread 2's Tx ends, but commit fails, because value of bal in memory does not match the read log, Tx needs to rerun

Concurrency Control

Pessimistic

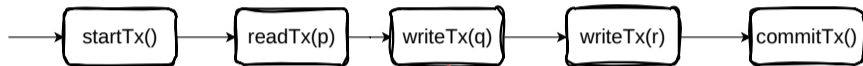
- Occurrence, detection, and resolution happen at the same time during execution
- Claims ownership of data before modifications

Optimistic

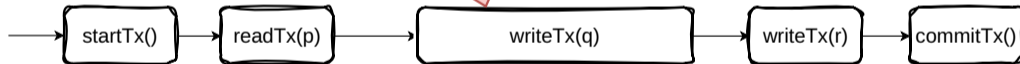
- Conflict detection and resolution can happen after the conflict occurs
- Multiple conflicting transactions can continue to keep running, as long as the conflicts are detected and resolved before the Txn commit

Pessimistic Concurrency Control

Thread 1



Thread 2

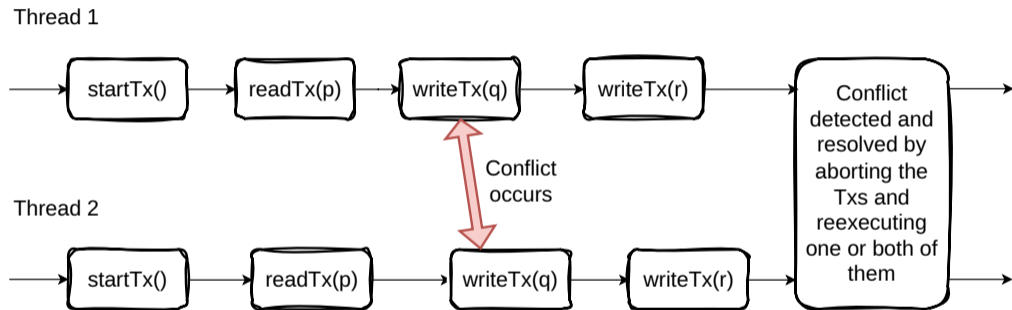


Conflict occurs, is detected, and is resolved by delaying Thread 2's Tx

Time of Locking

- When the Tx first accesses a location
- When the Tx is about to commit

Optimistic Concurrency Control



Pessimistic vs Optimistic Concurrency Control

Pessimistic

- Usually claims exclusive ownership of data before accessing
- Needs to avoid or detect and recover from deadlock situations
- + Effective in high contention cases

Optimistic

- Avoids claiming exclusive ownership of data, provides more conflict resolution choices
- Needs to avoid livelock situations through contention management schemes
- + Effective in low contention cases

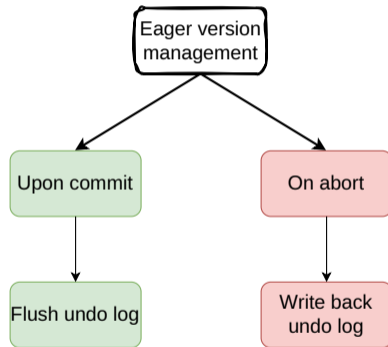
Hybrid Concurrency Control

- Use pessimistic control for writes and optimistic control for reads
- Use optimistic control TM with pessimistic control of irrevocable Tx
 - ▶ Irrevocable Tx means that the changes cannot be rolled back
 - ▶ A Tx that has performed I/O or a Tx that has experienced frequent conflicts in the past

Version Management

TMs need to track updates for conflict resolution

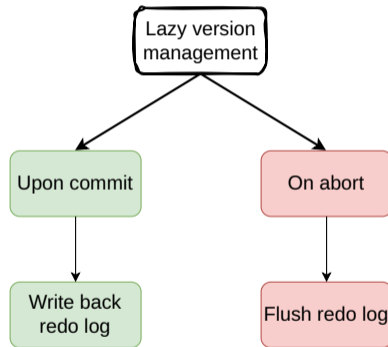
- Eager
 - ▶ Tx directly updates data in memory (direct update)
 - ▶ Maintains an undo log with overwritten values
 - ▶ Values in the undo log are used to revert updates on an abort



Version Management

TMs need to track updates for conflict resolution

- Lazy
 - ▶ Tx updates data in a private redo log
 - ▶ Updates are made visible at commit (deferred update)
 - ▶ Tx reads must look up redo logs
 - ▶ Discard redo log on an abort



Understanding Conflict Detection

- Pessimistic concurrency control is straightforward

Understanding Conflict Detection

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Understanding Conflict Detection

- Pessimistic concurrency control is straightforward
- Which concurrency control type should we use with eager version management, pessimistic or optimistic?

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Understanding Conflict Detection

- Pessimistic concurrency control is straightforward
- Which concurrency control type should we use with eager version management, pessimistic or optimistic?
- How do you check for conflicts in optimistic concurrency control?

Understanding Conflict Detection

- Pessimistic concurrency control is straightforward
- Which concurrency control type should we use with eager version management, pessimistic or optimistic?
- How do you check for conflicts in optimistic concurrency control?
 - ▶ Validation operation — Successful validation means Tx had no conflicts

Conflict Detection in Optimistic Concurrency Control

Conflict granularity

- Object or field in software TM, line offset or whole cache line in hardware TM
- What are the tradeoffs?

Time of conflict detection

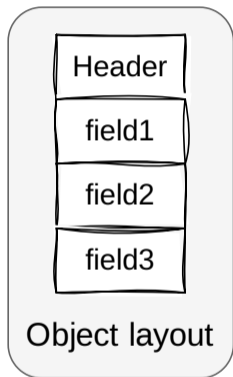
- Just before access (eager), during validation, during final validation before commit (lazy)
- Validation can occur at any time, and can occur multiple times

Conflicting access types

Among concurrent ongoing Txns, or between active and committed Txns

Object Layout

Object Model in Jikes RVM



```
|<- lo memory                                     hi memory ->|  
  
  SCALAR LAYOUT:  
|<----- scalar header ----->|  
+-----+-----+-----+-----+-----+-----+-----+  
| GCHheader | MiscHeader | JavaHeader | fld0 | fld1 | fldx | fldN-1 |  
+-----+-----+-----+-----+-----+-----+-----+  
                                     ^ JHOFF           ^objref  
                                     .  
                                     .  
  ARRAY LAYOUT:  
|<----- array header ----->|  
+-----+-----+-----+-----+-----+-----+-----+  
| GCHheader | MiscHeader | JavaHeader | len | elt0 | elt1 | ... |eltN-1|  
+-----+-----+-----+-----+-----+-----+-----+  
                                     ^ JHOFF           ^objref
```

Issues with Conflict Granularity

```
1 x = 0;  
2 y = 0;
```

Thread 1

```
1 do {  
2   startTx();  
3   tmp = readTx(&x);  
4   writeTx(x, 10);  
5 } while (!commitTx());
```

Thread 2

```
1 ...  
2 y = 20;  
3 ...  
4  
5
```

- Detect conflicts at the granularity of objects or fields
- A hardware technique can detect conflicts at the line/block level or at the level of individual byte offsets
- What are the tradeoffs?

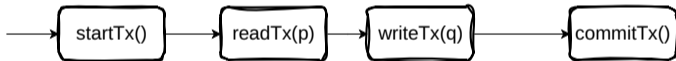
Transaction Semantics

Concurrency in TM

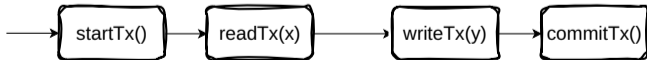
Two levels

- (i) Among Tx's from concurrent thread
- (ii) Among individual Tx operations

Thread 1



Thread 2

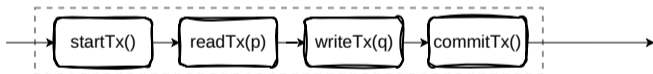


Serializability

The result of executing concurrent transactions must be identical to a result in which these transactions executed serially

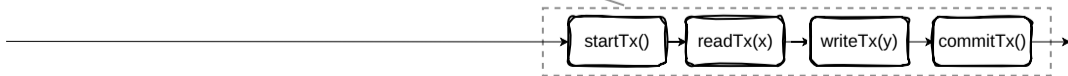
- Widely-used correctness condition in databases
- The TM system can reorder transactions
- Serializability requires the Txs appear to run in serial order
 - ▶ Does not require that the order has to be real-time

Thread 1



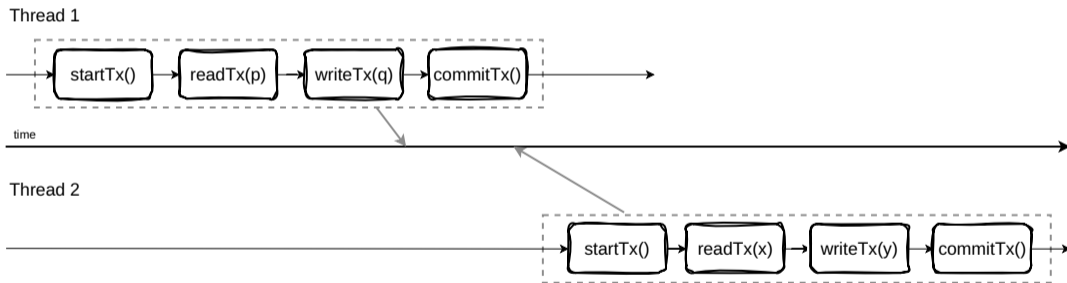
time

Thread 2

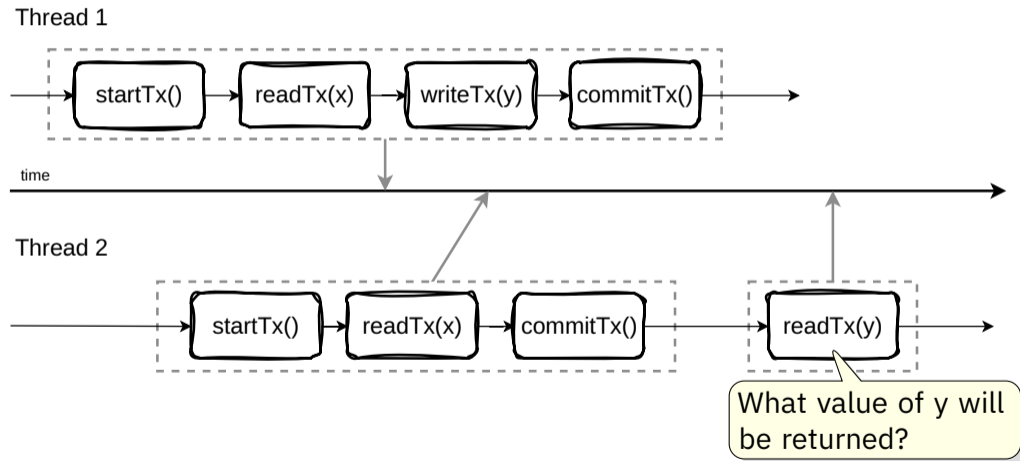


Strict Serializability

In strict serializability, if transaction TA completes before transaction TB starts, then TA must occur before TB in the equivalent serial execution

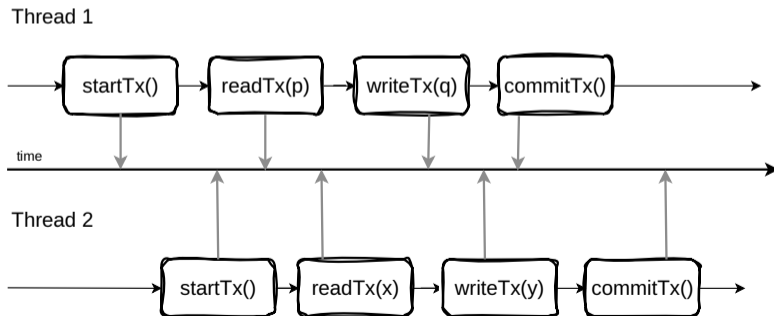


Limitations of Strict Serializability



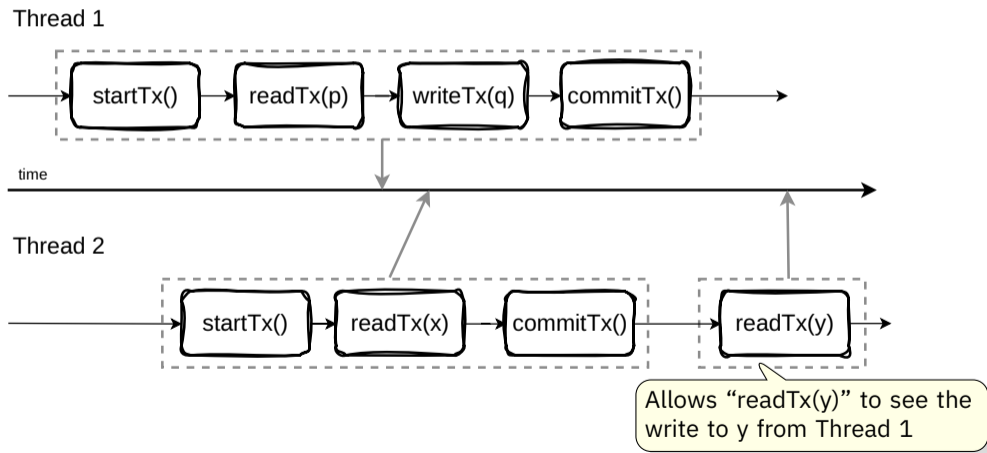
Linearizability

- A method call is the interval that starts with an invocation event and ends with a response event
- A method call is pending if the response event has not yet occurred
- Linearizability of an operation (e.g., method call): each operation appears to execute atomically at some point between its invocation and its completion



Linearizability

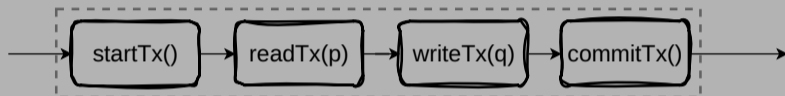
Linearizability of a transaction: a transaction is a single operation extending from the beginning of `startTx()` until the completion of its final `commitTx()`



Linearizability

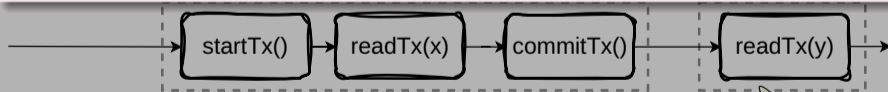
Linearizability of a transaction: a transaction is a single operation extending from the beginning of `startTx()` until the completion of its final `commitTx()`

Thread 1



time

If each transaction appears to execute atomically at a single instant, then conflicts between transactions will not occur



Allows “`readTx(y)`” to see the write to `y` from Thread 1

Snapshot Isolation (SI)

- Weaker isolation requirement than serializability
 - ▶ Can potentially allow greater concurrency between Txs
 - ▶ Many database implementations actually provide SI
- SI allows a Tx's reads to be serialized before the Tx's writes
- All reads must see a valid snapshot of memory
- Updates must not conflict

Example of SI

```
1 x = 0;  
2 y = 0;
```

Thread 1

```
1 do {  
2   startTx();  
3   int tmp_x = readTx(x);  
4   int tmp_y = readTx(y);  
5   int tmp = tmp_x + tmp_y + 1;  
6   writeTx(x, tmp);  
7 } while (!commitTx());
```

Thread 2

```
1 do {  
2   startTx();  
3   int tmp_x = readTx(x);  
4   int tmp_y = readTx(y);  
5   int tmp = tmp_x + tmp_y + 1;  
6   writeTx(y, tmp);  
7 } while (!commitTx());
```

What are possible values of x and y after execution?

- With serializability
- With SI

Understanding SI

```
1 X = 0;  
2 y = 0;
```

Thread 1

```
1 int t = x + 1; // 1  
2 x = t;
```

Thread 2

```
1 int t = x + 1; // 1  
2 x = t;
```

Sequentially consistent but no SI

Understanding SI

```
1 X = 0;  
2 y = 0;
```

Thread 1

```
1 x = 1;  
2 int t = y; // 0
```

Thread 2

```
1 y = 1;  
2 int t = x; // 0
```

SI but not sequentially consistent
and not serializable

Understanding SI

- Semantics of SI may seem unexpected when compared with simpler models based on serial ordering of complete transactions
- Potential increased concurrency often does not manifest as a performance advantage when compared with models such as strict serializability

Other TM Considerations

Consistency During Transactions

- Semantics such as serializability characterize the behavior of committed Tx
- What about the Tx which fail to commit?
 - ▶ Tx may abort or may be slow to reach `commitTx()`

Inconsistent Reads and Zombie Txns

```
1 x = 0;  
2 y = 0;
```

Assume eager version management
and lazy conflict detection

Thread 1

```
1 do {  
2   startTx();  
3   int tmp1 = readTx(&x);  
4  
5  
6  
7  
8  
9   int tmp2 = readTx(&y);  
10  while (tmp1 != tmp2) {}  
11 } while (!commitTx());
```

Thread 2

```
1  
2  
3  
4 do {  
5   startTx();  
6   writeTx(&x, 10);  
7   writeTx(&y, 10);  
8 } while (!commitTx());  
9  
10  
11
```

Inconsistent Reads and Zombie Txns

```
1 x = 0;  
2 y = 0;
```

Assume eager version management
and lazy conflict detection

Thread 1

```
1 do {  
2   startTx();  
3   int tmp1 = readTx(&x);  
4  
5  
6  
7  
8  
9   int tmp2 = readTx(&y);  
10  while (tmp1 != tmp2) {}  
11 } while (!commitTx());
```

Thread 2

```
1  
2  
3  
4 do {  
5   startTx();  
6   writeTx(&x, 10);  
7   writeTx(&y, 10);  
8 } while (!commitTx());  
9  
10
```

Validation only during commit is
insufficient for this TM design

Considerations with Zombie Tx

- A Tx that is inconsistent but is not yet detected is called a zombie Tx
- Careful handling of zombie Tx is required, especially for unsafe languages like C/C++
 - ▶ Inconsistent values can potentially be used in pointer arithmetic to access unwanted memory locations
- Possible workarounds: perform periodic validations
 - ▶ Increases run-time overhead, validating n locations once requires n memory accesses
 - ▶ Couples the program to the TM system
 - ▶ A TM using eager updates allows a zombie transaction's effects to become visible to other transactions
 - ▶ A TM using lazy updates only allows the effects of committed transactions to become visible

Challenges with Mixed-Mode Accesses

- TM semantics must consider the interaction between transactional and non-transactional memory accesses
- Many TMs do not detect conflicts between transactional and non-transactional accesses
 - ▶ Can lead to unexpected behavior with zombie Txs
- Requires the non-Tx thread to participate in conflict detection

Weak Atomicity

- Provides Tx semantics only among Txs
- Checks for conflicts only among Txs

Strong Atomicity

Guarantees Tx semantics among Txs and non-Txs

Think of Challenges with Weak Atomicity

- (i) Data races between Tx and non-Tx code
- (ii) Mismatched conflict detection granularity
 - ▶ Tx detects conflicts at a coarser granularity
- (iii) Complicated sharing idioms
 - ▶ Use a Tx to initialize shared data, expect other threads to read the data transactionally

Lock-Based Synchronization

- `java.util.LinkedList list` is shared
- Initially `list == [Itemval1==0, val2==0]`

Thread 1

```
1 Item item;  
2 synchronized(list) {  
3     item = list.removeFirst();  
4 }  
5 int r1 = item.val1;  
6 int r2 = item.val2;  
7
```

Thread 2

```
1 synchronized(list) {  
2     if (!list.isEmpty()) {  
3         Item item = list.getFirst();  
4         item.val1++;  
5         item.val2++;  
6     }  
7 }
```

Can we safely replace synchronize with atomic?

Consider a TM design with eager versioning and lazy conflict detection

- `java.util.LinkedList` list is shared
- Initially `list == [Item{val1==0, val2==0}]`

Thread 1

```
1 Item item;  
2 weakly_atomic(list) {  
3     item = list.removeFirst();  
4 }  
5 int r1 = item.val1;  
6 int r2 = item.val2;  
7
```

Thread 2

```
1 weakly_atomic(list) {  
2     if (!list.isEmpty()) {  
3         Item item = list.getFirst();  
4         item.val1++;  
5         item.val2++;  
6     }  
7 }
```

Few Issues to Consider with Weak Isolation

- Non-repeatable reads
- Intermediate lost updates
- Intermediate dirty reads
- Granular lost updates
- ...

Non-repeatable Reads

A non-repeatable read can occur if a Tx reads the same variable multiple times, and a non-Tx write is made to it in between.

Thread 1

```
1 atomic {  
2   r1 = x;  
3  
4   r2 = x;  
5 }
```

Thread 2

```
1  
2  
3 x = 1;  
4  
5
```

Unless the TM buffers the value seen by the first read, the transaction will see the update.

Intermediate Lost Update

An intermediate lost update can occur if a non-Tx write interposes in a transactional read-modify-write sequence. The non-Tx write can be lost, without being seen by the Tx read.

```
1 x = 0;
```

Thread 1

```
1 atomic {  
2   r = x;  
3  
4   x = r + 1;  
5 }
```

Thread 2

```
1  
2  
3 x = 10;  
4  
5
```


Intermediate Dirty Read

An intermediate dirty read can occur with a TM using eager version management in which a non-Tx read sees an intermediate value written by a transaction, rather than the final, committed value.

```
1 assert (x%2 == 0); // even
```

Thread 1

```
1 atomic {  
2   x++;  
3  
4   x++;  
5 }
```

Thread 2

```
1  
2  
3 r = x;  
4  
5
```

Single-Lock Atomicity for Transactions

- How do we provide semantics for mixed-mode accesses?
- A program executes as if all transactions acquire a single, program-wide mutual exclusion lock

Thread 1

```
1 startTx();  
2 while (true) {}  
3 commitTx();
```

Thread 2

```
1 startTx();  
2 int tmp = readTx(&x);  
3 commitTx();
```

What will happen with SLA?

There are many other proposed models like DLA and TSC

Nested Transactions

- Nested parallelism is important
 - ▶ Utilizes increasing number of cores
 - ▶ Integrates with programming models like OpenMP
- Execution of a nested Tx is wholly contained in the dynamic extent of another Tx
- Many choices on how nested Txs interact
 - ▶ Flattened
 - ▶ Aborting the inner Tx causes the outer Tx to abort
 - ▶ Committing the inner Tx has no effect until the outer Tx commits
 - ▶ Closed
 - ▶ Inner Tx can abort without terminating its parent Tx

```
1 // Parallelize loops
2 FOR I := ...
3   FOR J := ...
4     FOR K := ...
```

```
1 int x = 1;
2 do {
3   StartTx();
4   WriteTx(&x, 2);
5   do {
6     StartTx();
7     WriteTx(&x, 3);
8     AbortTx();
9     ...
```

Providing Txns: TM Implementations

Software Transactional Memory (STM)

Hardware Transactional Memory (HTM)

STM

- + Supports flexible techniques in TM design
- + Easy to integrate STMs with PL runtimes
- + Easier to support unbounded Txns with dynamically-sized logs
- More expensive than HTMs

HTM

- Restricted variety of implementations
- Need to adapt existing runtimes to make use of HTM
- Limited by bounded-sized structures like caches
- + Better performance than STMs

Software Transactional Memory

Software Transactional Memory (STM)

Data structures

- Need to maintain per-thread Tx state
- Maintain either redo log or undo log
- Maintain per-Tx read/write sets

- McRT-STM, PPOPP'06
- Bartok-STM, PLDI'06
- JudoSTM, PACT'07
- RingSTM, SPAA'08

- NoRec STM, PPOPP'10
- DeuceSTM, HiPEAC'10
- LarkTM, PPOPP'15
- ...

We love questions?

Remember well-designed applications should have low conflict rates

- Is the design of undo log important in a TM with eager version management?

We love questions?

Remember well-designed applications should have low conflict rates

- Is the design of undo log important in a TM with eager version management?
- Is the design of redo log important in a TM with lazy version management?

Implementing STM

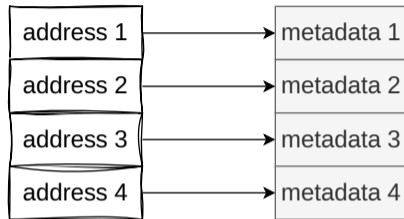
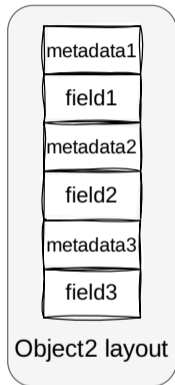
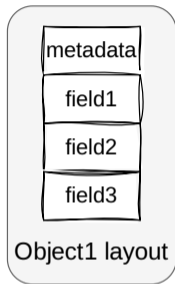
- Use compilation passes to instrument the program
 - `startTx()` Tx entry point (prologue)
 - `commitTx()` Tx exit point (epilogue)
 - `readTx()` Tx read access
 - `writeTx()` Tx write access
- TM runtime tracks memory accesses, detects conflicts, and commits/aborts Tx

```
1 atomic {  
2     tmp = x;  
3     y = tmp + 1;  
4 }
```

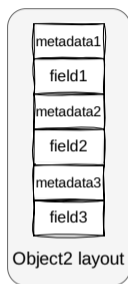
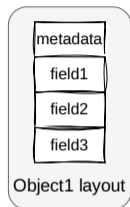


```
1 // Per-TX data structure  
2 td = getTxDesc(thr);  
3 startTx(td);  
4 tmp = readTx(&x);  
5 writeTx(&y, tmp+1);  
6 commitTx(td);
```

Object Metadata and Word Metadata



Pros and Cons of Metadata in Object Header



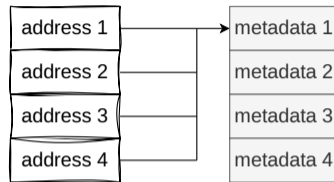
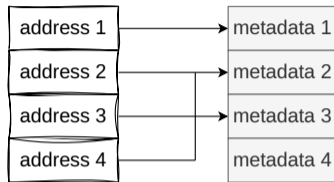
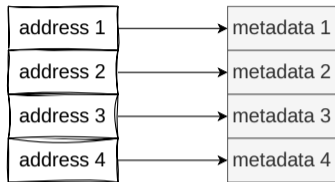
Pro

- + May lie on the same cache line
- + Single update for accesses to all fields

Con

- Potential for false conflicts
- Increases coupling (e.g., complicates GC)

Variants of Word-based Metadata



Use hash functions to map addresses to a fixed-size metadata space

Process-wide metadata space

Which granularity to use?

Potential impact due to false conflicts

Impact on memory usage

Impact on performance, i.e., speed of mapping location to metadata

Major STM Designs

Per-object versioned locks (McRT-STM, Bartok-STM)

- Use locks for protecting updates, and use versions to detect conflicts involving reads

Global clock with per-object metadata (TL2)

Fixed global metadata (JudoSTM, RingSTM, NOrec STM)

Nonblocking STMs (DSTM)

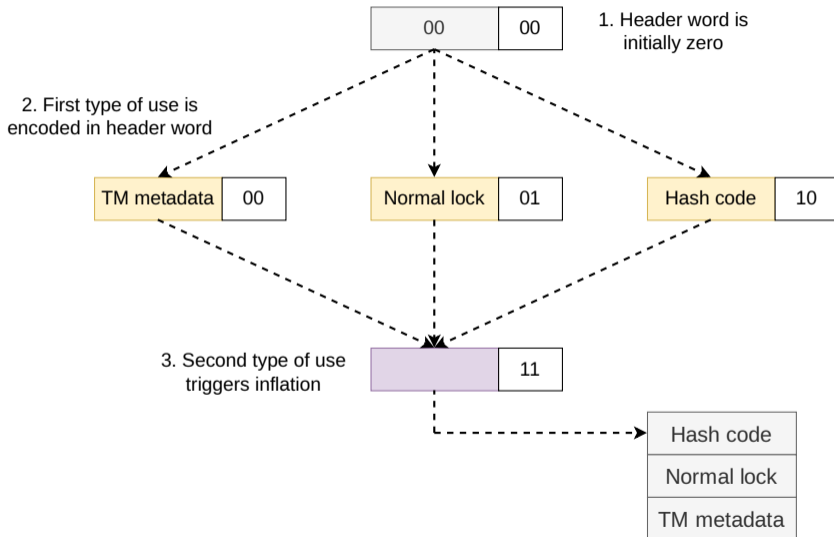
- Does not use locks

Lock-Based STM with Versioned Reads

High-level design

- Pessimistic concurrency control for writes
 - ▶ Locks are acquired dynamically
- Optimistic concurrency control for reads
 - ▶ Validation using per-object version numbers

Header Word Optimizations in Bartok STM



Other Design Choices

- Eager vs lazy version management
- Access-time locking or commit-time locking
- Access-time locking
 - ▶ Can support both eager or lazy version management
 - ▶ Detects conflicts between active transactions, irrespective of whether they ultimately commit
- Commit-time locking
 - ▶ Can support only lazy version management

STM Metadata

- Versioned locks
 - Lock mutual exclusion of writes
 - Version number detect conflicts involving reads
- Lock is available — no pending writes, holds the current version of the object
- Lock is taken — refers to the owner Tx
- Invisible reads — presence of a reading Tx is not visible to concurrent Txs which might try to commit updates to the objects being read

Read and Write Operations

```
1 readTx(tx, obj, off) {
2   tx.readSet.obj = obj;
3   tx.readSet.ver = getVerFromMd(obj);
4   tx.readSet++;
5
6   return read(obj, off);
7 }
```

eager version
management

```
1 writeTx(tx, obj, off, newVal) {
2   acquire(obj);
3
4   tx.undoLog.obj = obj;
5   tx.undoLog.offset = off,
6   tx.undoLog.val = read(obj, off);
7   tx.undoLog++;
8
9   tx.writeSet.obj = obj;
10  tx.writeSet.off = off;
11  tx.writeSet.ver = ver;
12  tx.writeSet++;
13
14  write(obj, off, newVal);
15  release(obj);
16 }
```

Read and Write Operations

```
1 readTx(tx, obj, off) {  
2   tx.readSet.obj = obj;  
3   tx.readSet.ver = getVerFromMd(obj);  
4   tx.readSet++;  
5  
6   return read(obj, off);  
7 }
```

```
1 writeTx(tx, obj, off, newVal) {  
2   acquire(obj);  
3   undoLogInt(tx, obj, off);  
4   tx.writeSet.obj = obj;  
5   tx.writeSet.off = off;  
6   tx.writeSet.ver = ver;  
7   tx.writeSet++;  
8   write(obj, off, newVal);  
9   release(obj);
```

type specialization

```
12 undoLogInt(tx, obj, off) {  
13   tx.undoLog.obj = obj;  
14   tx.undoLog.offset = off,  
15   tx.undoLog.val = read(obj, off);  
16   tx.undoLog++;  
17 }
```

Conflict Detection on Writes

Writes

Reads

How do you detect conflicts on writes?

Conflict Detection on Reads

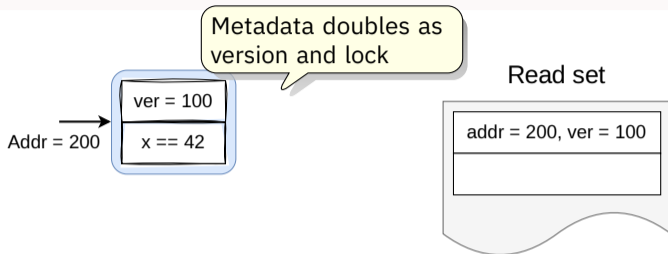
Writes

Reads

```
1 bool commitTx(tx) {  
2     foreach (entry e in tx.readSet)  
3         if (!validateTx(e.obj, e.ver))  
4             abortTx(tx);  
5     return false;  
6     foreach (entr e in tx.writeSet)  
7         unlock(e.obj, e.ver);  
    return true;  
}
```

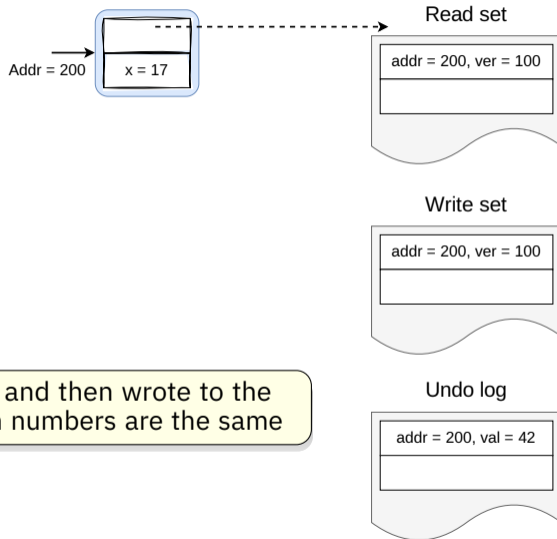
Unlock increments the version number

No Conflict on Read from Addr=200



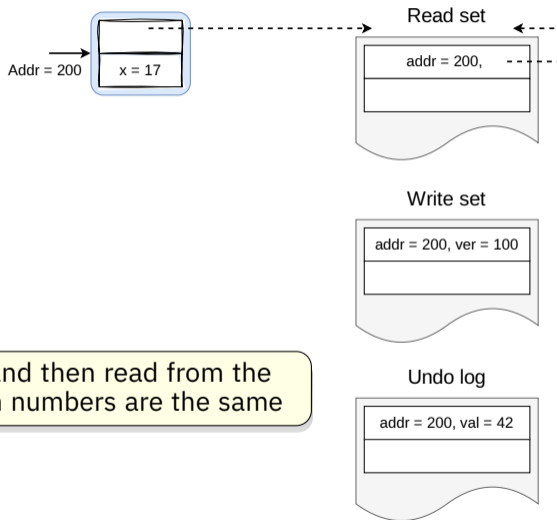
Transaction read from the object, and its version number is unchanged at commit time

No Conflict on Read from and Write to Addr=200



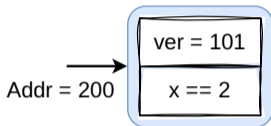
Transaction read from and then wrote to the object, and the version numbers are the same

No Conflict on Write to and Read from Addr=200

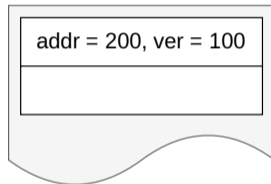


Transaction wrote to and then read from the object, and the version numbers are the same

Conflict on Read from Addr=200, Concurrent Tx Updates and Commits

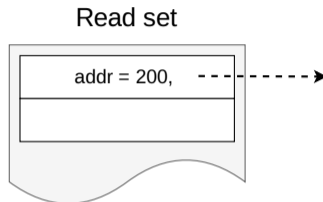
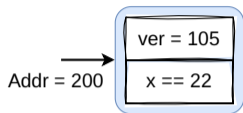


Read set



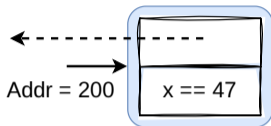
Transaction read from the object, and there is a version mismatch during `commitTx()`

Conflict on Read from Addr=200, Concurrent Write

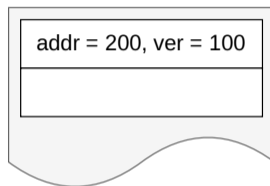


Transaction read from the object when it was owned by some other Tx

Conflict on Read from Addr=200 during Commit

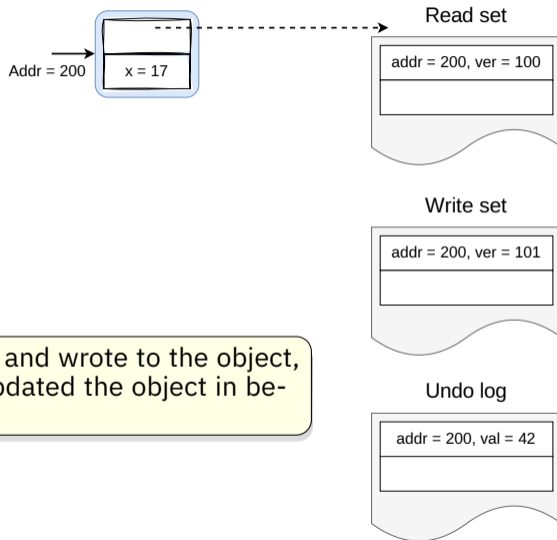


Read set



Transaction is owned by some other Tx when the current reader Tx tries to commit

Conflict Between Read and Write from Addr=200



Transaction read from and wrote to the object, but a concurrent Tx updated the object in between

Practical Issues

Version overflow

- Theoretical concern, is a practical concern if the metadata is “packed”
- Globally renumber objects if overflow is rare
- Distinguish between an “old” and a wrapped-around “new” version
 - ▶ Ensure that each thread validates its current Tx at least once within n version increments

Do these techniques (McRT, Bartok) allow zombie txs?

Semantics of McRT and Bartok

Read set may not remain consistent during txs

Does not detect conflicts between txs and non-txs

Hardware Transactional Memory

Hardware Transactional Memory (HTM)

- Can provide strong isolation without modifications to non-Tx accesses
- Easy to extend to unmanaged languages
- TCC, ISCA'04
- LogTM, HPCA'06
- Rock HTM, ASPLOS'09
- FlexTM, ICS'09
- Azul HTM
- Intel TSX
- IBM Blue Gene/Q

Possible ISA Extensions

Similar to STMs, HTMs need to demarcate Tx boundaries and transactional memory accesses

Explicit

- `begin_transaction`
- `end_transaction`
- `load_transactional`
- `store_transactional`

Memory accessed within a Tx through ordinary memory instructions do not participate in any transactional memory protocol

Implicit

- `begin_transaction`
- `end_transaction`

All memory accesses are transactional

Possible ISA Extensions

Similar to STMs, HTMs need to demarcate Tx boundaries and transactional memory accesses

Explicit

- `begin_transaction`
- `end_transaction`
- `load_transactional`
- `store_transactional`

Memory accessed within a Tx through ordinary memory instructions do not participate in any transactional memory protocol

Implicit

- `begin_transaction`
- `end_transaction`

All memory accesses are transactional

Which is simpler?

Explicitly vs Implicitly Transactional HTMs

Explicitly Transactional

- Provides flexibility to choose desired memory locations
 - ▶ Reduced read and write set size
- May require multiple library versions
 - ▶ Limits reuse of legacy libraries in HTMs

Implicitly Transactional

- Larger read and write sets
- Easy to reuse software libraries

Design Issues in HTMs

Tracking read and write sets

- Introducing additional structures like transactional cache complicates the data path
- Recent ideas extend existing data caches to track accesses
 - ▶ Granularity matters (one read bit for a cache line)
- Need to be careful with writes

Conflict detection

- Natural to piggyback on cache coherence protocols to detect conflicts
- Most HTMs detect conflicts eagerly, and transfer control to a software handler

Intel Transactional Synchronization Extensions (TSX)

- TSX supported by Intel in selected series based on Haswell microarchitecture
- TSX hardware can dynamically determine whether threads need to serialize lock-protected critical sections

High-Level Goal with Transactions

- Hardware dynamically determines whether threads need to serialize
 - ▶ For example, with lock-protected critical sections
- Hardware serializes only when required
- Thus, processor exposes and exploits concurrency that is hidden due to unnecessary synchronization
- Lock elision idea introduced by Ravi Rajwar and James R. Goodman in 2001
 - ▶ Remove locks, run code as a transaction
 - ▶ If there are conflicts, abort and rerun code with locks intact
 - ▶ On success, commit the transaction's writes to memory

Intel Transactional Synchronization Extensions

TSX operation

- Optimistically executes critical sections eliding lock operations
- Commit if the Tx executes successfully
- Otherwise abort — discard all updates, restore architectural state, and resume execution
- Resumed execution may fall back to locking

Hardware Lock Elision (HLE)

- xacquire
- xrelease

Extends HTM support to legacy hardware

Restricted Transactional Memory (RTM)

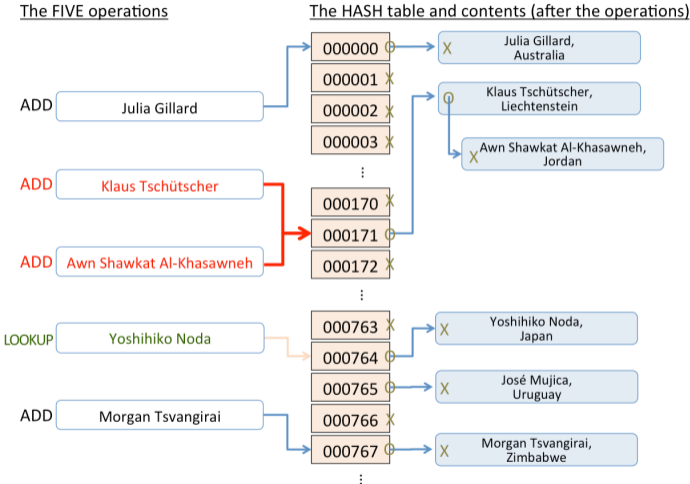
- xbegin
- xend
- xabort

New ISA extensions

Hardware Lock Elision (HLE)

- Application uses legacy-compatible prefix hints to identify critical sections
 - ▶ Hints ignored on hardware without TSX
- HLE provides support to execute critical section transactionally without acquiring locks
- Abort causes a re-execution without lock elision
- Hardware manages all state

Goal with Intel TSX



Lock Acquire Code

```
1 acquire(mutex);  
2 /* critical section */  
3 release(mutex);
```

} application

```
1 mov eax, 1  
2 Try: lock xchg mutex, eax  
3 cmp eax, 0  
4 jz Success  
5 Spin: pause  
6 cmp mutex, 1  
7 jz Spin  
8 jmp Try
```

```
1 mov mutex, 0
```

HLE Interface

```
1 acquire(mutex);  
2 /* critical section */  
3 release(mutex);
```

} application

```
1 mov eax, 1  
2 Try: xacquire lock xchg mutex, eax  
3 cmp eax, 0  
4 jz Success  
5 Spin: pause  
6 cmp mutex, 1  
7 jz Spin  
8 jmp Try
```

```
1 xrelease mov mutex, 0
```

Restricted Transactional Memory (RTM)

- Software uses new instructions to identify critical sections
 - ▶ Similar to HLE, but more flexible interface for software
 - ▶ Requires programmers to provide an alternate fallback path
- Processor may abort RTM transactional execution for several reasons
- Abort transfers control to target specified by XBEGIN operand
 - ▶ Abort information encoded in the EAX GPR

RTM Interface

```
1 Retry: xbegin Abort
2       cmp mutex, 0
3       jz Success
4       xabort $0xff
```

5
6 Abort:

```
7     // check eax and do retry
8     // policy actually acquire
9     // lock or wait to retry
10    ...
```

acquire(mutex)

```
1     mov eax, 1
2 Try:  lock xchg mutex, eax
3       cmp eax, 0
4       jz Success
```

```
5  
6 Spin: pause
7       cmp mutex, 1
8       jz Spin
9       jmp Try
```

10

```
1     cmp mutex, 0
2     jnz Rel
3     xend
```

```
1 Rel:  mov mutex, 0
```

```
2  
3
```

release(mutex)

XTEST Instruction

Queries whether the logical processor is transactionally executing in a transactional region identified by either HLE or RTM

Aborts in TSX

- Conflicting accesses from different cores (data, locks, false sharing)
 - ▶ TSX maintains read/write sets at the granularity of cache lines
- Capacity misses
- Some instructions always cause aborts (system calls, I/O)
- Eviction of a transactionally-written cache line
- Eviction of transactionally-read cache lines do not cause immediate aborts
 - ▶ Backed up in a secondary structure which might overflow

Finding Reasons for Aborts can be Hard

EAX register bit position	Meaning
0	Set if abort caused by XABORT instruction
1	If set, the transaction may succeed on a retry. This bit is always clear if bit 0 is set.
2	Set if another logical processor conflicted with a memory address that was part of the transaction that aborted.
3	Set if an internal buffer overflowed
4	Set if debug breakpoint was hit
5	Set if an abort occurred during execution of a nested transaction
23:6	Reserved
31:24	XABORT argument (only valid if bit 0 set, otherwise reserved)

TSX Implementation Details

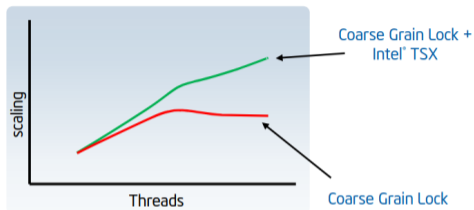
- Every detail is not known
 - ▶ Read and write sets are at cache line granularity
 - ▶ Uses L1 data cache as the storage
- Conflict detection is through cache coherence protocol

TSX caveats

- No guarantees that Txs will commit
- There should be a software fallback independent of TSX to guarantee forward progress

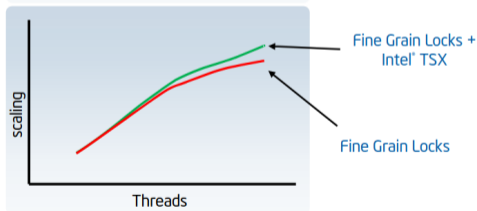
Applying Intel TSX

Application with Coarse Grain Lock



Application re-written with Finer Grain Locks







An example of secondary benefits of Intel[®] TSX



Relevance of TSX-like Concepts

- GNU glibc 2.18 added support for lock elision of pthread mutexes of type `PTHREAD_MUTEX_DEFAULT`
- Glibc 2.19 added support for elision of read/write mutexes
 - ▶ Depends whether the `-enable-lock-elision=yes` parameter was set at compilation time of the library
- Java JDK 8u20 onward support adaptive elision for synchronized sections when the `-XX:+UseRTMLocking` option is enabled
- Intel Thread Building Blocks (TBB) 4.2 supports elision with the `speculative_spin_rw_mutex`

References

-  T. Harris et al. Transactional Memory. 2nd edition, Morgan Kaufmann.
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-  A. Kleen. Adding lock elision to Linux. Linux Plumbers Conference, 2012.
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