# Lecture 11: Transactional Memory
active research:
here there be dragons

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## Challenges of Synchronization

- Two major issues:
  - Performance
    - Scalability
    - Base cost
    - We've looked at some techniques that address this
      - Better spinlocks
      - Lockless strategies (NBS, RCU)
  - Programmability
    - Locks are hard to use correctly
    - Lockless data structures are hard to design



## What's missing?

- Lack of support for *abstraction* and *composition*
- E.g. Suppose we have thread-safe stack with (abstract) push and pop operations
  - In sequential programs, can use these operations without regard to their implementation
  - In parallel programs, internal details may be needed
    - Consider task of moving an item from one stack to another
    - Need to expose stack locking mechanism



## "Magic" Wish List

- Let programmers express desired outcome (i.e. "This block of code should appear atomic")
- Let run-time system or hardware support make it happen
- Allow abstractions to hide implementation and be composable

☞ A new programming model is needed

## Database Transactions

- Database systems allow multiple queries to run in parallel
- Query authors don't worry about concurrency
- Complex queries can be composed out of simpler ones
- Key Programming Model: everything is a transaction
  - A transaction executes as if it were the only computation accessing the database
  - Atomic – all updates become visible, or none
  - Consistent – transactions leave database in consistent state
  - Isolated – no interference with or from other transactions
  - Durable – once committed, updates are permanent

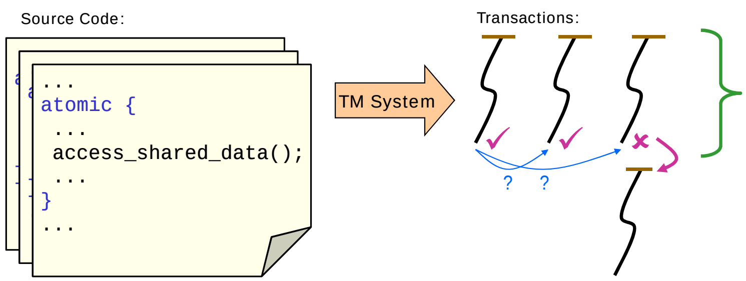


## Transactional Memory: Some History

- 1977 – D.B. Lomet (IBM Research, now at Microsoft Research) suggests database transaction model for concurrent programming
  - No practical implementation provided
- 1983 – Kung & Robinson propose *optimistic concurrency control* for databases
- 1988 – Chang & Mergen describe IBM 801 storage manager
  - HW provided lock bits for each 128 byte range of a page; page tables & TLB extended
- 1993 – Herlihy & Moss describe a hardware proposal for *transactional memory*



## Transactional Memory (TM)




Programmer: Specifies threads/transactions in source code
TM System: Executes transactions optimistically in parallel
1) Checkpoints execution
2) Detects conflicts
3) Commits or aborts and re-executes



## Differences from DB Transactions

- Memory vs. disk
  - Disk access takes 100X longer than memory access → database systems can use relatively heavy-weight software solutions
- No need for durability
  - Memory is transient anyway → simplifies TM implementations
- Existing languages, libraries and systems
  - Databases are closed systems in which all code executes as a transaction, programs using TM must coexist with libraries, OSs that do not

## TM Implementations

- Hardware TM (HTM)
  - Changes to computer system and ISA
  - Extra cache to buffer writes, extended coherence protocol to track conflicts, special transaction instructions
  - Support for limited number of memory locations
- Software TM (STM)
  - Language runtime (or library) + extensions to specify trans.
  - Exploit current commodity hardware (multicores)
  - Get experience with transactional programming model
  - Java: DSTM (Marathe et al.), ASTM (Herlihy et al.)
  - C/C++: McRT-STM (Saha et al.), TL2 (Dice et al.), RSTM
- Hybrid TM (HyTM)



## Programming Constructs

- Atomic block

```
atomic {
  if (x!=null) x.foo();
  y = true;
}
```

- Delimits code that should execute in a transaction
- Dynamically-scoped – code in foo executes in transaction as well
- Does not name shared resources (unlike monitors or lock-based programming)
- 3 possible outcomes – commits, aborts, non-termination



## Caution!

- Programmers can still use this construct incorrectly

```
bool flagA=false; bool flagB=false
```

*Thread 1:*

```
atomic {
  while (!flagA);
  flagB = true;
}
```

*Thread 2:*

```
atomic {
  flagA = true;
  while (!flagB);
}
```

- Deadlock results



## Semantics

- Not yet formally specified!
- Useful ways to reason about TM:
  - Database correctness criteria: serializability
    - Useful for understanding transaction behavior
    - Says nothing about interaction of transactions with code outside of transactions
  - Operational semantics – single-lock atomicity
    - Program executes as if all atomic blocks were protected by single global lock
    - Does not capture failure atomicity
    - Can describe effect of non-transactional accesses
      - Conflict and data race concepts from lock-based programming

## Additional Considerations

- Weak vs. Strong Atomicity (or isolation)
  - Weak – conflicting memory reference outside transaction may not follow protocols of TM system
  - Strong – all operations outside atomic blocks are converted into individual transactions, guaranteeing all accesses obey TM protocols
  - Equivalent w.r.t semantics of single-lock atomicity in programs without data races
- Nested transactions – required for composability
  - Flattened – inner transaction essentiall removed
  - Closed – effect of inner transaction only visible to surrounding one; abort affects only inner
  - Open – effect of inner becomes visible to all after commit; abort affects only inner



## Implementation Basics

- For all (non-stack) write instructions:
  - Track write addresses and values (*write set*)
- For all (non-stack) read instructions:
  - track read addrs and values (*read set*)
- When a transaction completes:
  - Atomically
    - Validate read set (conflict detection)
    - Commit write set

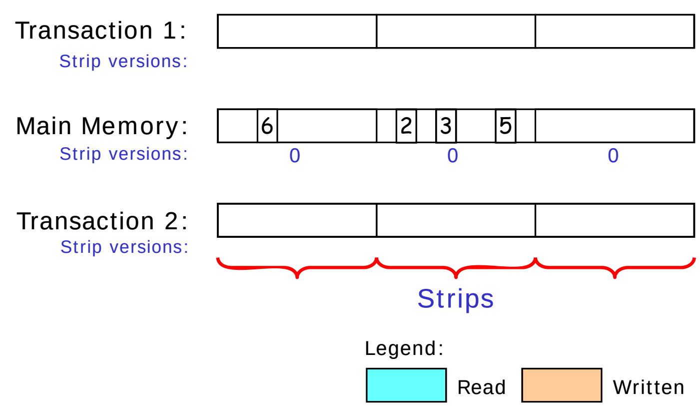


## Implementation Options

- Transaction Granularity
  - Unit of storage over which TM system detects conflicts
  - Akin to notion of cache coherence
  - Word or block typical for HTM, object common for STMs that extend OO language
- Direct or Deferred Update
  - Direct – transaction directly modifies the object itself
    - Must log previous value for undo in case of abort
  - Deferred – modify private copy, propagate at commit
  - Both get complicated in the presence of data races
- Optimistic or Pessimistic Concurrency Control
  - TM typically optimistic; need to detect and resolve conflict



## Location-Based Conflict Detection



## Location-Based Conflict Detection

**Transaction 1:** 2 3 5
Strip versions:

Main Memory: 6 2 3 5
Strip versions: 0 0 0

Transaction 2:
Strip versions:

Legend: Read Written

## Location-Based Conflict Detection

Transaction 1: 2 3 5
Strip versions: 0

Main Memory: 6 2 3 5
Strip versions: 0 0 0 ✓

**Transaction 2:** 6 9
Strip versions: 0

Commit step 1) Validate Read Set ✓

Commit step 2) Publish Writes (and inc version #s)

Legend: Read Written

## Location-Based Conflict Detection

**Transaction 1:** 2 3 5
Strip versions: 0 ✗

Main Memory: 6 9 3 5
Strip versions: 0 1 0

Transaction 2:
Strip versions: 0

Commit step 1) Validate Read Set ✗ Abort!

Note: all transactions must maintain strip version #s

Legend: Read Written

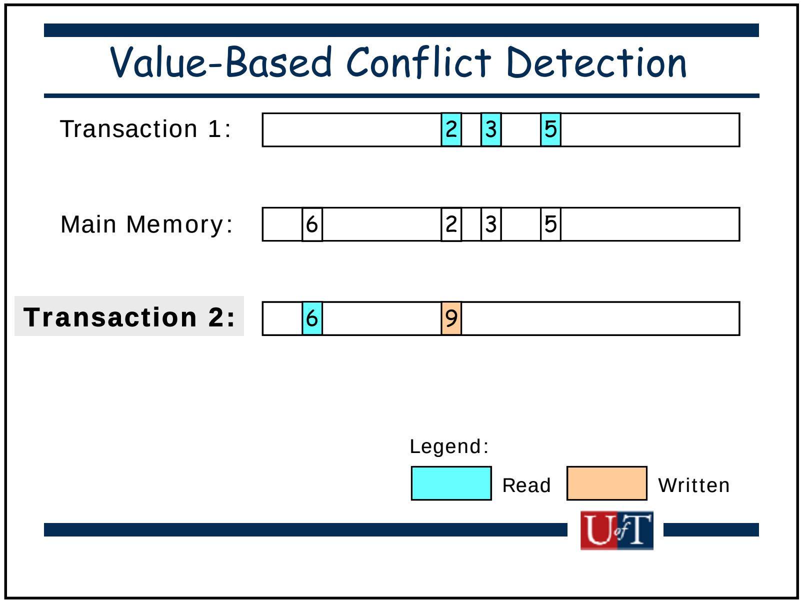
## Value-Based Conflict Detection

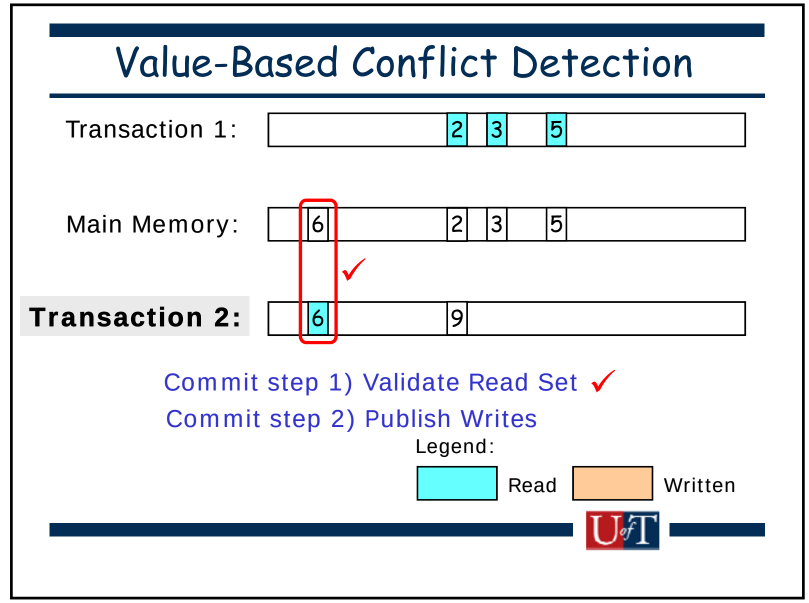
**Transaction 1:** 2 3 5

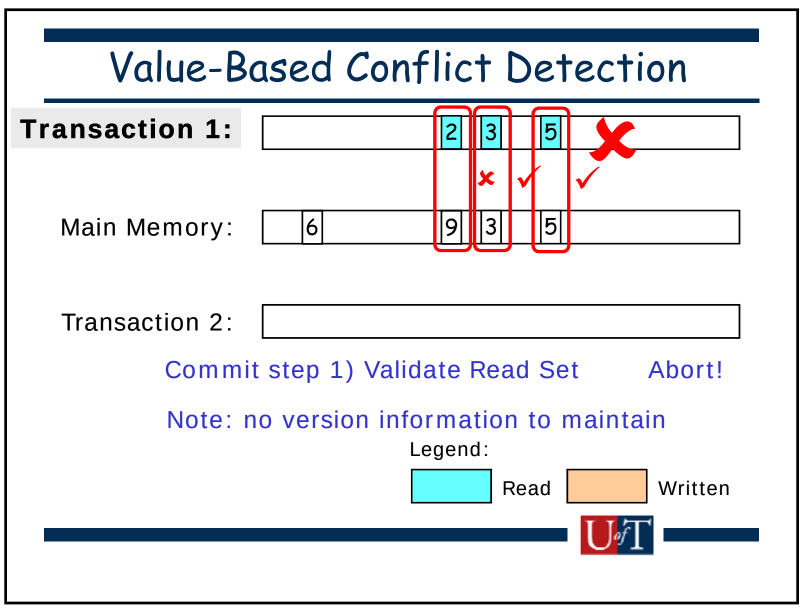
Main Memory: 6 2 3 5

Transaction 2:

Legend: Read Written


Value-Based Conflict Detection
Transaction 1:
2
3
5
Main Memory:
6
2
3
5
Transaction 2:
6
9
Legend:
Read
Written


Value-Based Conflict Detection
Transaction 1:
2
3
5
Main Memory:
6
2
3
5
Transaction 2:
6
9
Commit step 1) Validate Read Set ✓
Commit step 2) Publish Writes
Legend:
Read
Written


Value-Based Conflict Detection
Transaction 1:
2
3
5
Main Memory:
6
9
3
5
Transaction 2:
Commit step 1) Validate Read Set
Abort!
Note: no version information to maintain
Legend:
Read
Written