Transactional Memory

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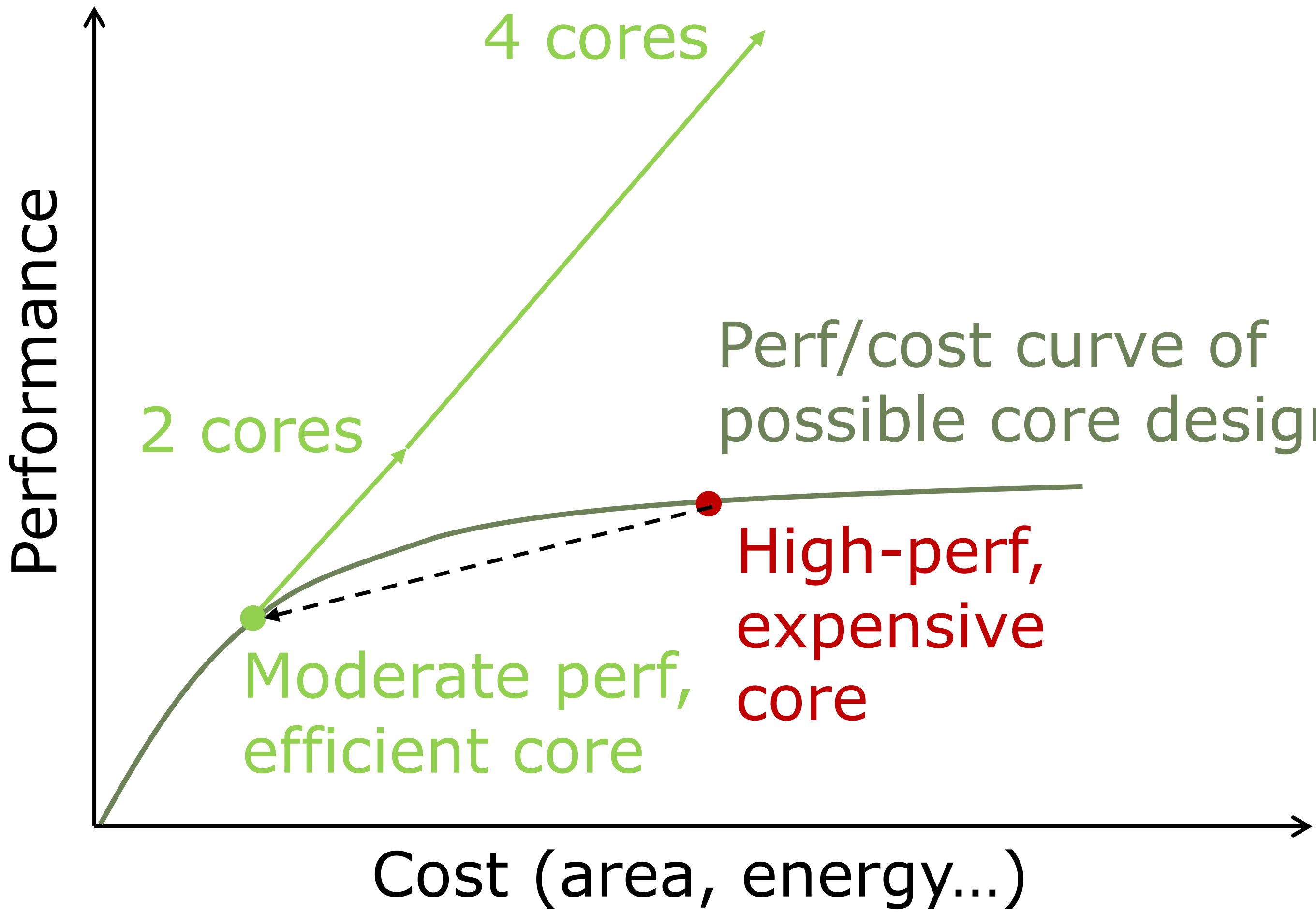
Based on slides from Christos Kozyrakis

Reminder: Why Multicore?



But Parallel Programming is HARD

- Divide algorithm into tasks
- Map tasks to threads
- Add synchronization (locks, barriers, …) to avoid data races and ensure proper task ordering

- Pitfalls: scalability, locality, deadlock, livelock, fairness, races, composability, portability…

Example: Hash Table

- Sequential implementation:

```
V lookup(K key)  {
  int idx = hash(key);
  for (;; idx++) {
   if (buckets[idx].empty)
    return NOT_FOUND;
   if (buckets[idx].key == key)
    return buckets[idx].val;
  }
}
```

- Not thread-safe
  - e.g., concurrent inserts and lookups cause races
  - Need synchronization

Thread-Safe Hash Table with Coarse-Grain Locks

```
V lookup(K key)  {
  int idx = hash(key);
  V result = NOT_FOUND;
  lock(mutex);
  for (;; idx++) {
    if (buckets[idx].empty) break;
    if (buckets[idx].key == key) {
      result = buckets[idx].val;
      break;
    }
  }
  unlock(mutex);
  return result;
}
```

- Also add lock(mutex)/unlock(mutex) pairs to all other hash table methods (insert, remove, …)
- *Problem?* Serializes operations to independent buckets

Thread-Safe Hash Table with Fine-Grain Locks

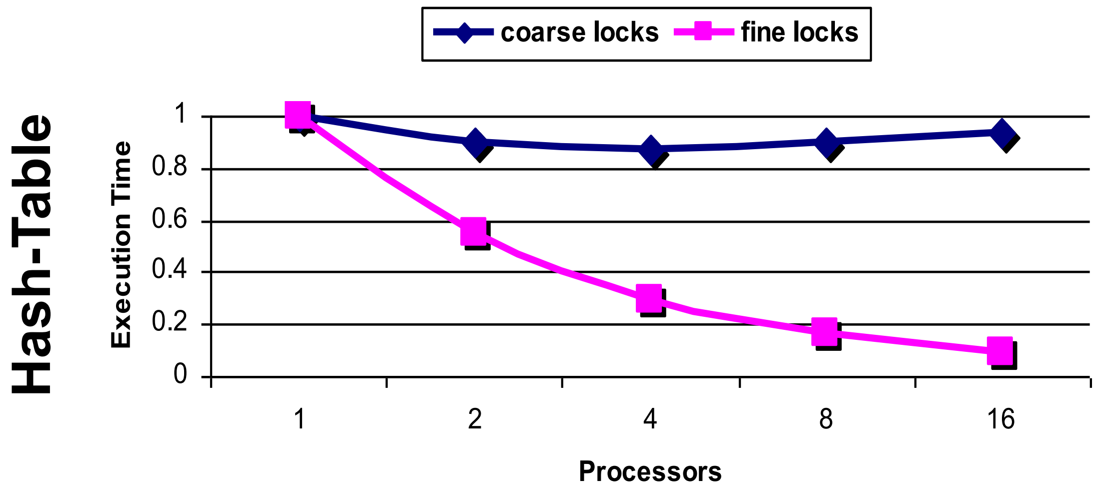
```
V lookup(K key)  {
  int idx = hash(key);
  V result = NOT_FOUND;
  for (;; idx++) {
    lock(buckets[idx].mutex);
    if (buckets[idx].empty) {
      unlock(buckets[idx].mutex);
      break;
    }
    if (buckets[idx].key == key) {
      result = buckets[idx].val;
      unlock(buckets[idx].mutex);
      break;
    }
    unlock(buckets[idx].mutex);
  }
  return result;
}
```

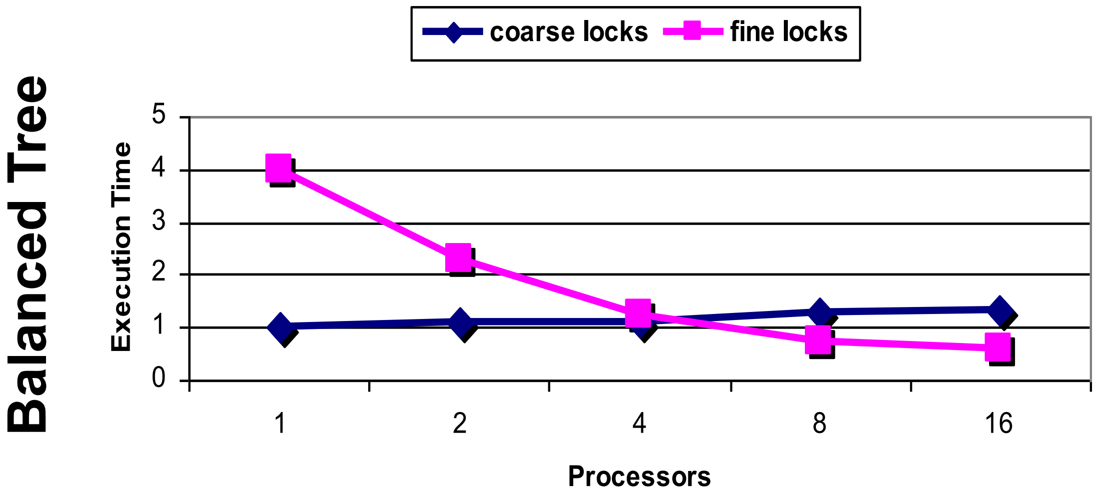
- Per-bucket locks
- *Problems?*

Locking overheads

Still overserializes!
(e.g., concurrent reads to the same bucket)

Performance: Locks





Concurrency Control

- We need to implement concurrency control to avoid races on shared data!

- Options?
  - Stall
    - Mutual exclusion: Ensure at most one process in critical section; others wait

  - Speculate
    - Guess: No conflicts will occur during the critical section
    - Check: Detect whether conflicting data accesses occur
    - Recover: If conflict occurs, roll back; otherwise commit

Transactional Memory (TM)

- Memory transaction [Lomet'77, Knight'86, Herlihy & Moss'93]
  - An atomic & isolated sequence of memory accesses
  - Inspired by database transactions

- Atomicity (all or nothing)
  - At commit, all memory writes take effect at once
  - On abort, none of the writes appear to take effect
- Isolation
  - No other code can observe writes before commit
- Serializability
  - Transactions seem to commit in a single serial order
  - The exact order is not guaranteed

Programming with TM

```
void deposit(account, amount) {
   lock(account.mutex);
   int t = bank.get(account);
   t = t + amount;
   bank.put(account, t);
   unlock(account.mutex);
}
```

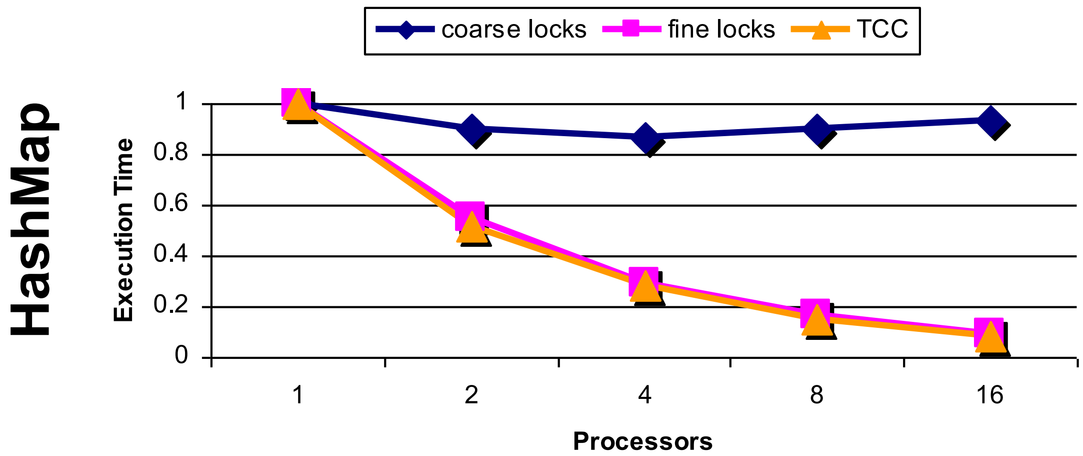
```
void deposit(account, amount) {
   atomic {
     int t = bank.get(account);
     t = t + amount;
     bank.put(account, t);
   }
}
```

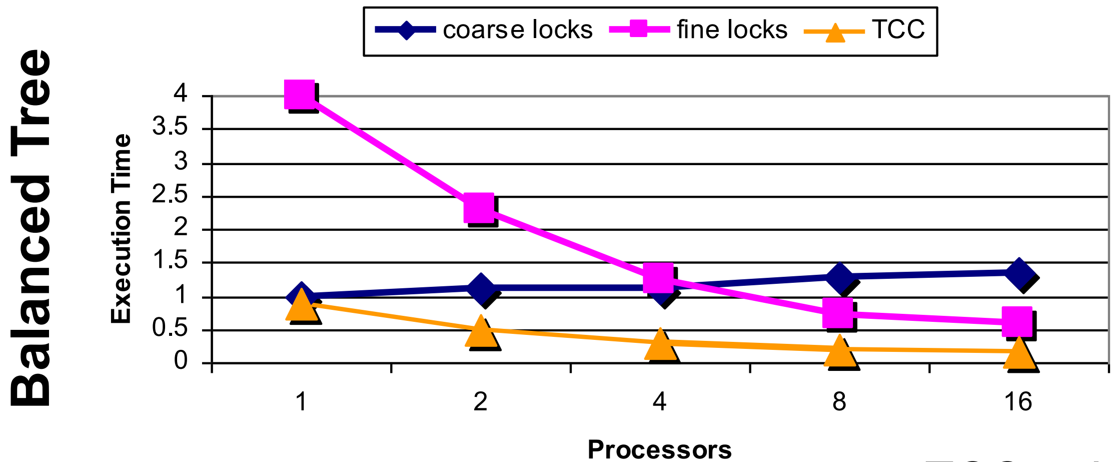
- Declarative synchronization
  - Programmers says what but not how
  - No declaration or management of locks
- System implements synchronization
  - Typically through speculation
  - Performance hit only on conflicts (R-W or W-W)

Advantages of TM

- Easy-to-use synchronization
  - As easy to use as coarse-grain locks
  - Programmer declares, system implements
- High performance
  - Performs at least as well as fine-grain locks
  - Automatic read-read & fine-grain concurrency
  - No tradeoff between performance & correctness
- Composability
  - Safe & scalable composition of software modules (nested transactions)

Performance: Locks vs Transactions





TCC: a HW-based TM system
[Hammond et al, ISCA'04]

TM Implementation Basics

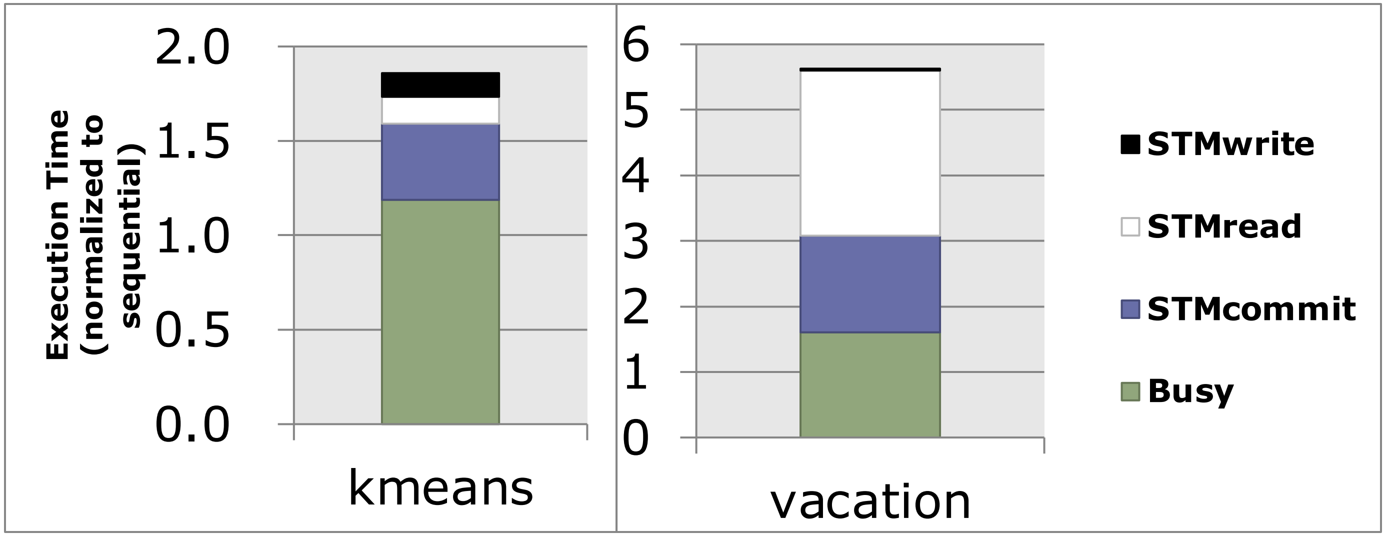
- Use speculation to provide atomicity and isolation without sacrificing concurrency

- Basic implementation requirements
  - Data versioning
  - Conflict detection & resolution

- Implementation options
  - Hardware transactional memory (HTM)
  - Software transactional memory (STM)
  - Hybrid transactional memory
    - Hardware accelerated STMs and dual-mode systems

Motivation for Hardware TM

- Single-thread software TM performance:



- Software TM suffers 2-8x slowdown over sequential
  - Short-term issue: demotivates parallel programming
  - Long-term issue: not energy-efficient

- Industry adopting Hardware TM: Intel (since Haswell), IBM (POWER8+, Blue Gene, zSeries), ARM (v9)

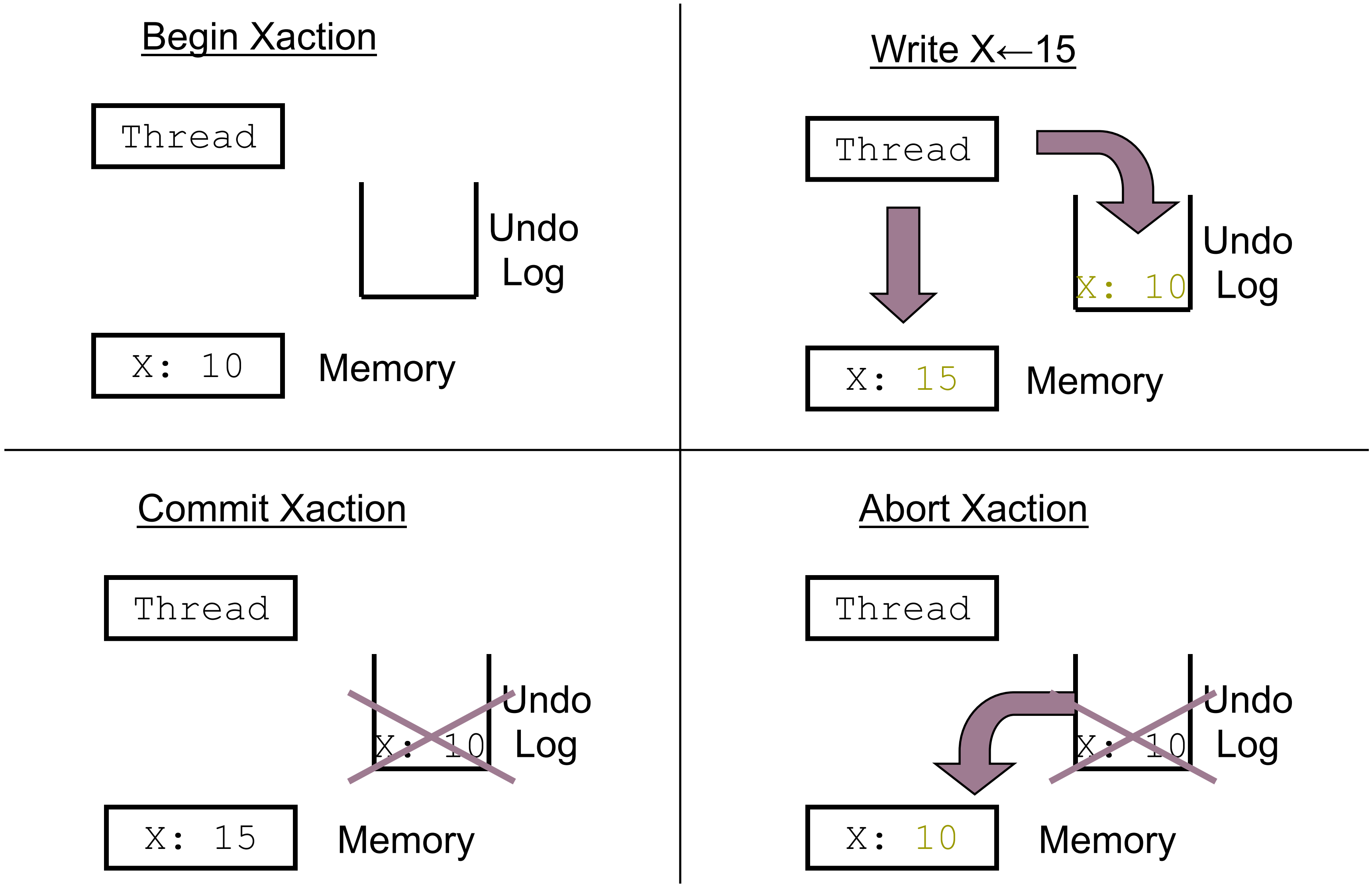
Data Management Policy

- Manage uncommitted (new) and committed (old) versions of data for concurrent transactions

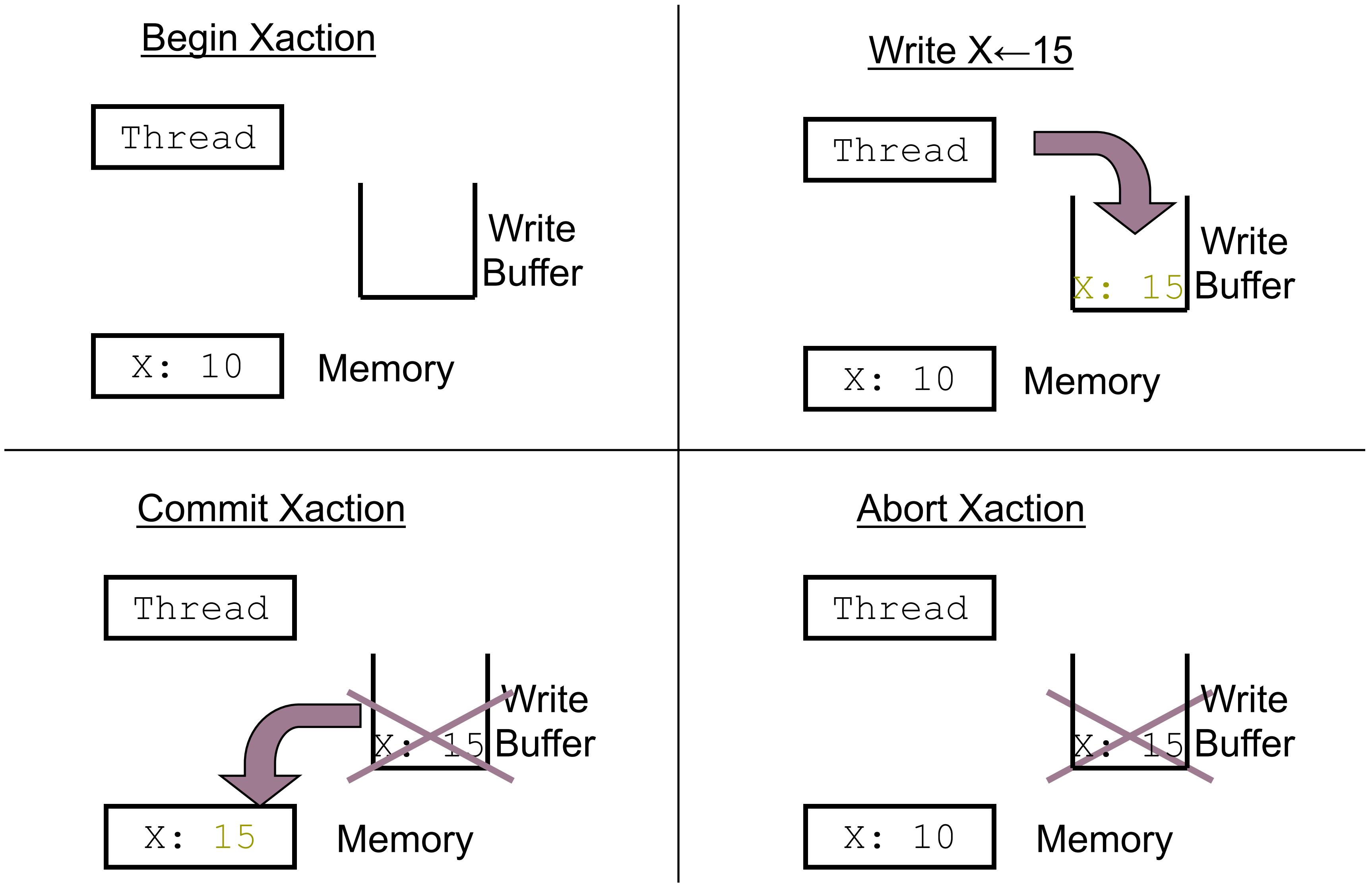
1. Eager versioning (undo-log based)
   - Update memory location directly
   - Maintain undo info in a log
   - + Fast commits
   - – Slow aborts

2. Lazy versioning (write-buffer based)
   - Buffer data until commit in a write buffer
   - Update actual memory locations at commit
   - + Fast aborts
   - – Slow commits

Eager Versioning Illustration



Lazy Versioning Illustration

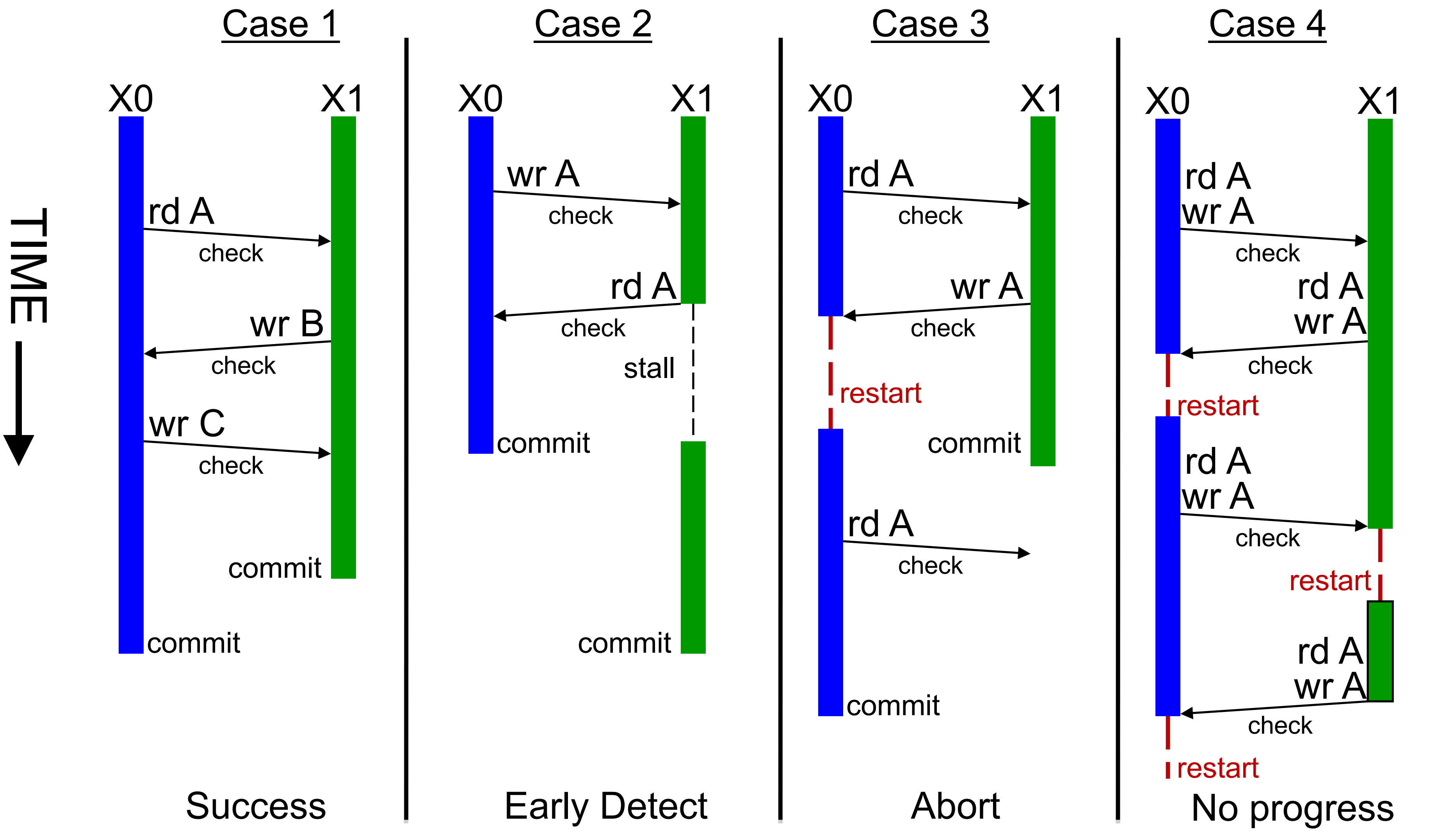


Conflict Detection

- Detect and handle conflicts between transaction
  - Read-Write and (often) Write-Write conflicts
  - Must track the transaction’s read-set and write-set
    - Read-set: addresses read within the transaction
    - Write-set: addresses written within transaction

1. Pessimistic detection
   - Check for conflicts during loads or stores
     - SW: SW barriers using locks and/or version numbers
     - HW: check through coherence actions
   - Use contention manager to decide to stall or abort
     - Various priority policies to handle common case fast

Pessimistic Detection Illustration

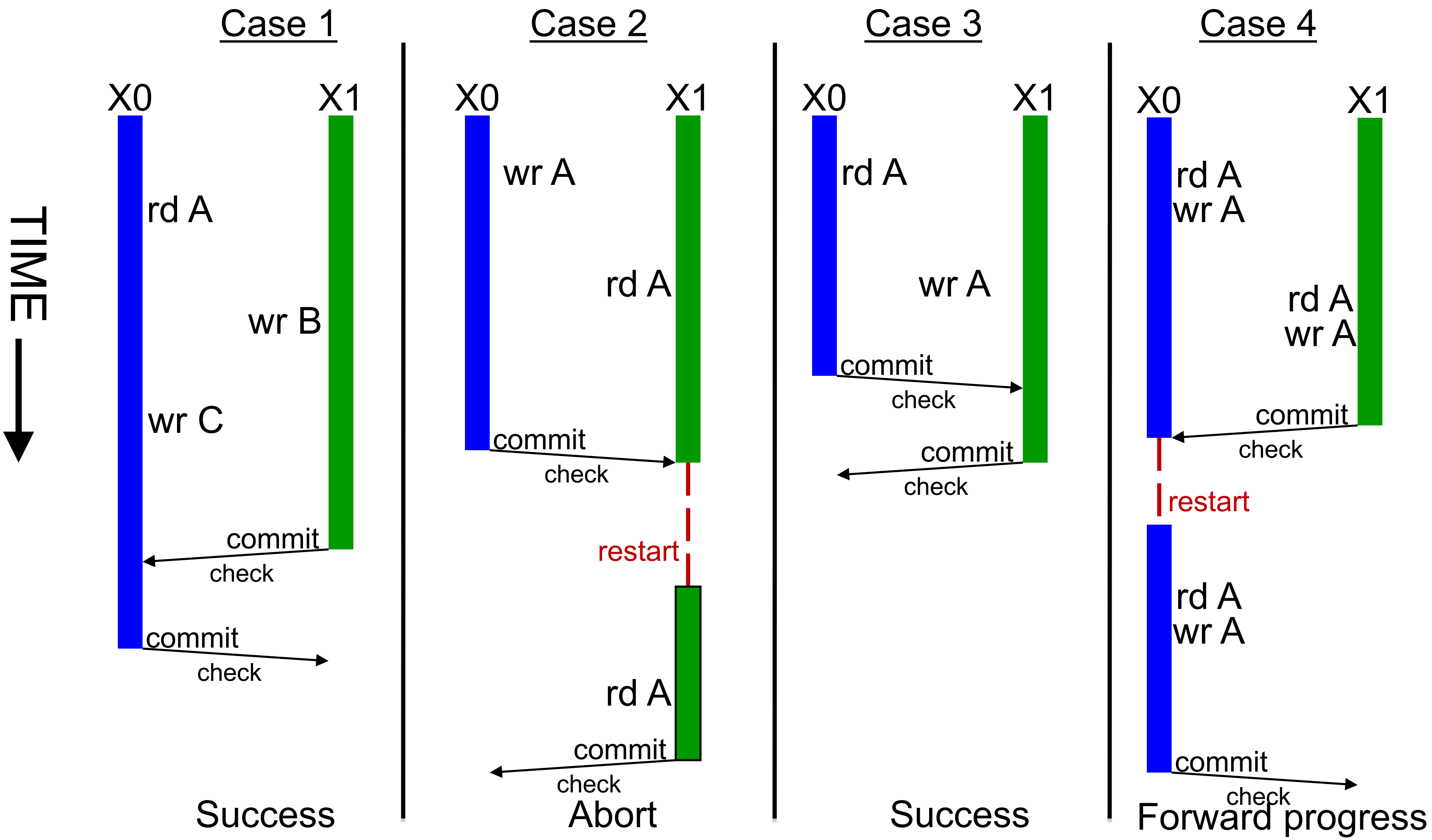


Conflict Detection (cont.)

2. Optimistic detection
   - Detect conflicts when a transaction attempts to commit
   - SW: validate write/read-set using locks or version numbers
   - HW: validate write-set using coherence actions
     - Get exclusive access for cache lines in write-set
     - On a conflict, give priority to committing transaction
     - Other transactions may abort later on
   - On conflicts between committing transactions, use contention manager to decide priority

- Note: optimistic & pessimistic schemes together
  - Several STM systems are optimistic on reads, pessimistic on writes

Optimistic Detection Illustration



Conflict Detection Tradeoffs

1. Pessimistic conflict detection
   - + Detect conflicts early
     - Undo less work, turn some aborts to stalls
   - – No forward progress guarantees, more aborts in some cases
     - Requires additional techniques to guarantee forward progress (e.g., backoff, prioritize older transactions)
   - – Locking issues (SW), fine-grain communication (HW)

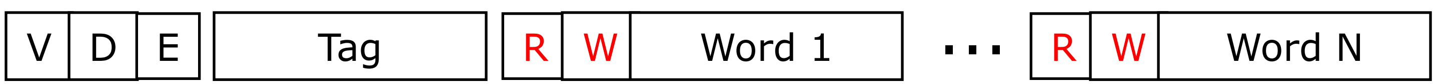
2. Optimistic conflict detection
   - + Forward progress guarantees
   - + Potentially less conflicts, shorter locking (SW), bulk communication (HW)
   - – Detects conflicts late, still has fairness problems

HTM Implementation Overview

- Data versioning: Use caches
  - Cache the write-buffer or the undo-log
  - Cache metadata to track read-set and write-set
  - Can do with private, shared, and multi-level caches
- Conflict detection: Use the cache coherence protocol
  - Coherence lookups detect conflicts between transactions
  - Works with snooping & directory coherence
- Note: On aborts, must also restore register state → take register checkpoint
  - OOO cores support with minimal changes (recall rename table snapshots…)

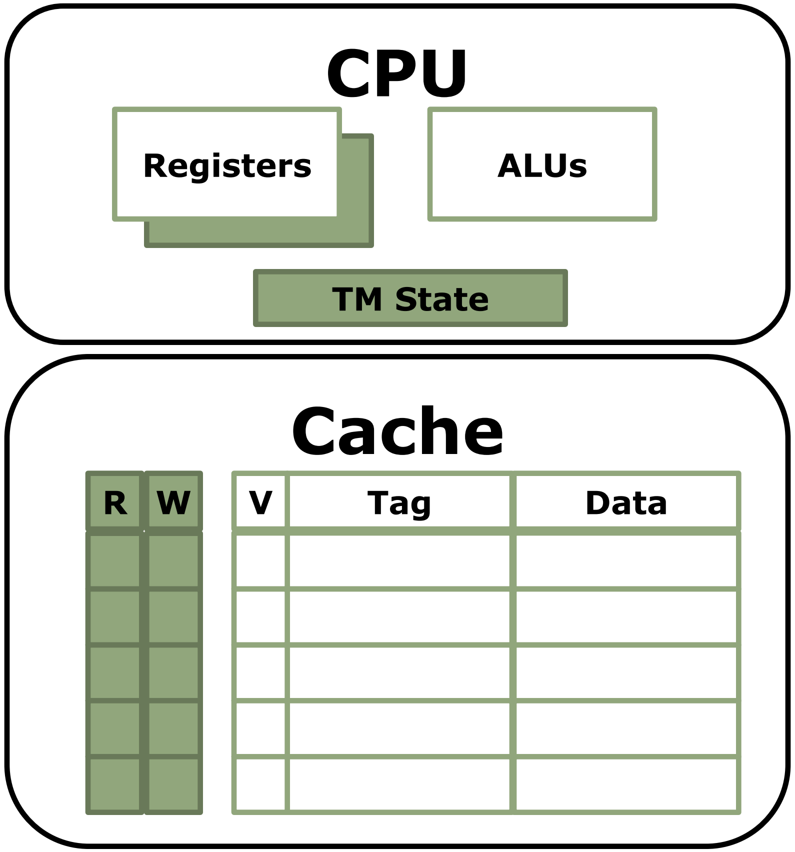
HTM Design

- Cache lines track read-set & write-set
  - R bit: indicates data read by transaction; set on load
  - W bit: indicates data written by transaction; set on store
  - R/W bits can be at word or cache-line granularity
  - R/W bits gang-cleared on transaction commit or abort



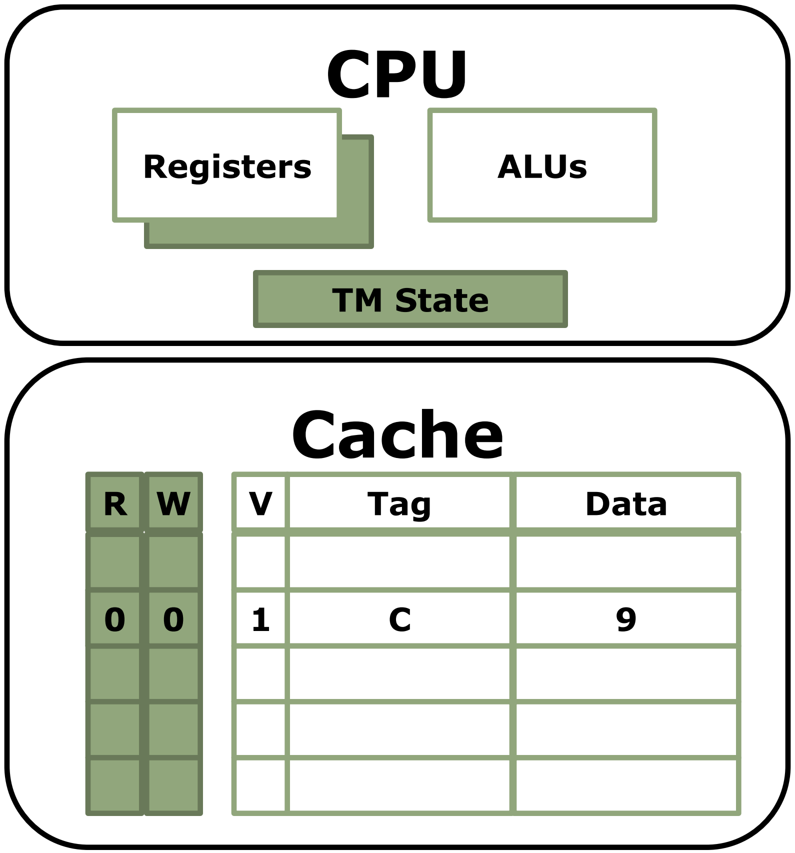
- Coherence requests check R/W bits to detect conflicts
  - Shared request to W-word is a read-write conflict
  - Exclusive request to R-word is a write-read conflict
  - Exclusive request to W-word is a write-write conflict

Example HTM: Lazy Optimistic



- CPU changes
  - Register checkpoint
  - TM state registers (status, pointers to handlers, …)
- Cache changes
  - Per-line R/W bits
- Assume a bus-based system

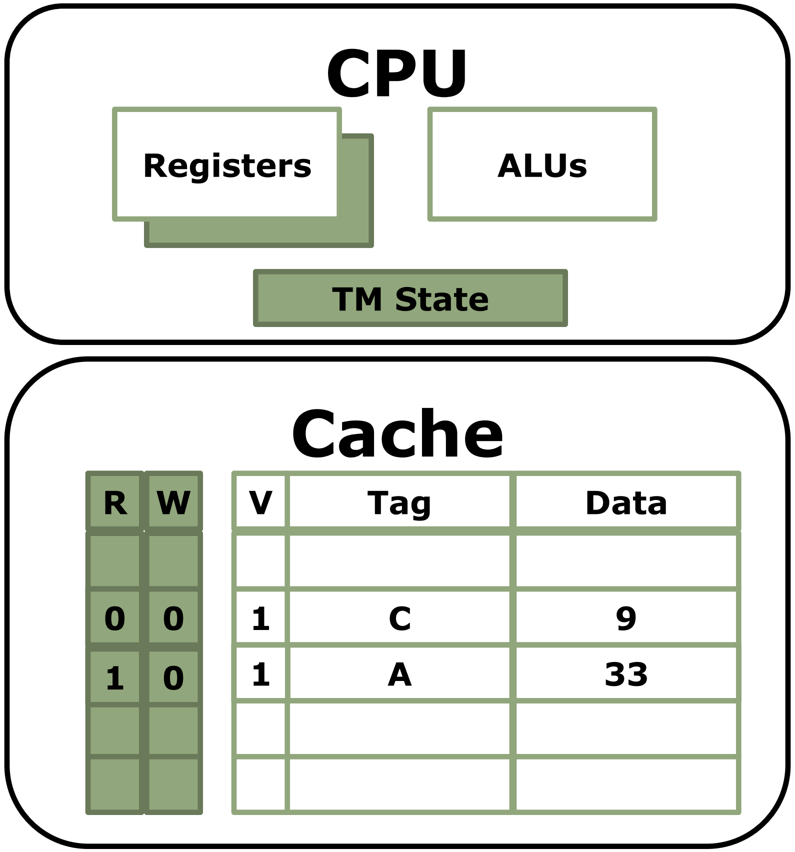
HTM Transaction Execution




```
Xbegin  ⇦
    Load A
    Store B ⇐ 5
    Load C
Xcommit
```

- Transaction begin
  - Initialize CPU & cache state
  - Take register checkpoint

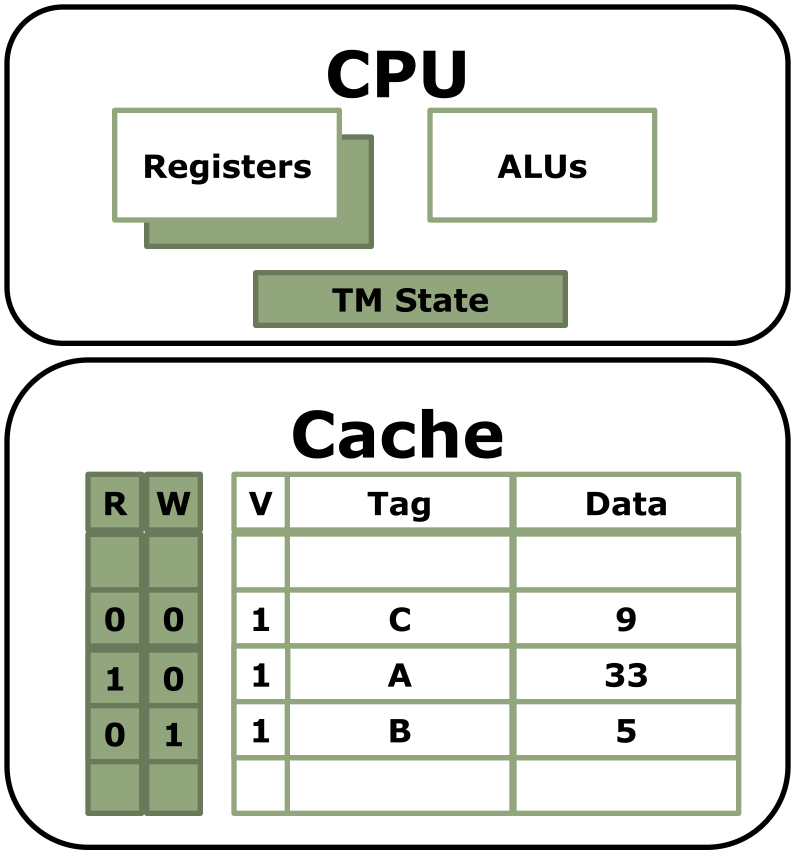
HTM Transaction Execution




```
Xbegin
    Load A ⇦
    Store B ⇐ 5
    Load C
Xcommit
```

- Load operation
  - Serve cache miss if needed
  - Set line's R-bit

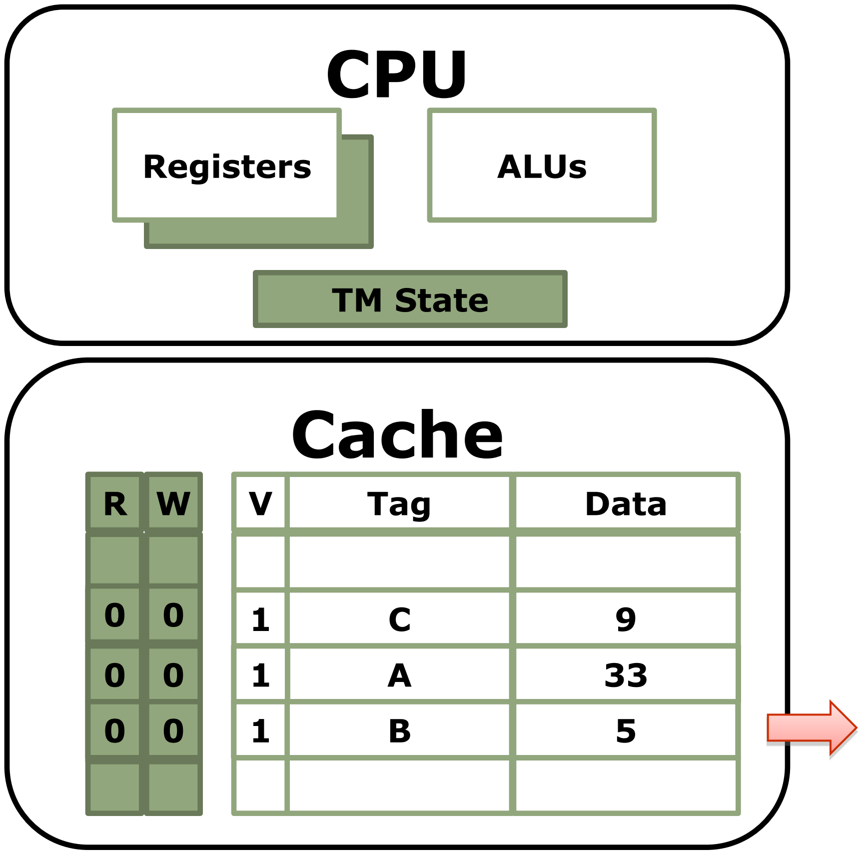
HTM Transaction Execution




```
Xbegin
    Load A
    Store B ⇐ 5
    Load C
Xcommit
```

- Store operation
  - Serve cache miss if needed (if other cores have line, get it shared anyway!)
  - Set line’s W-bit

HTM Transaction Execution

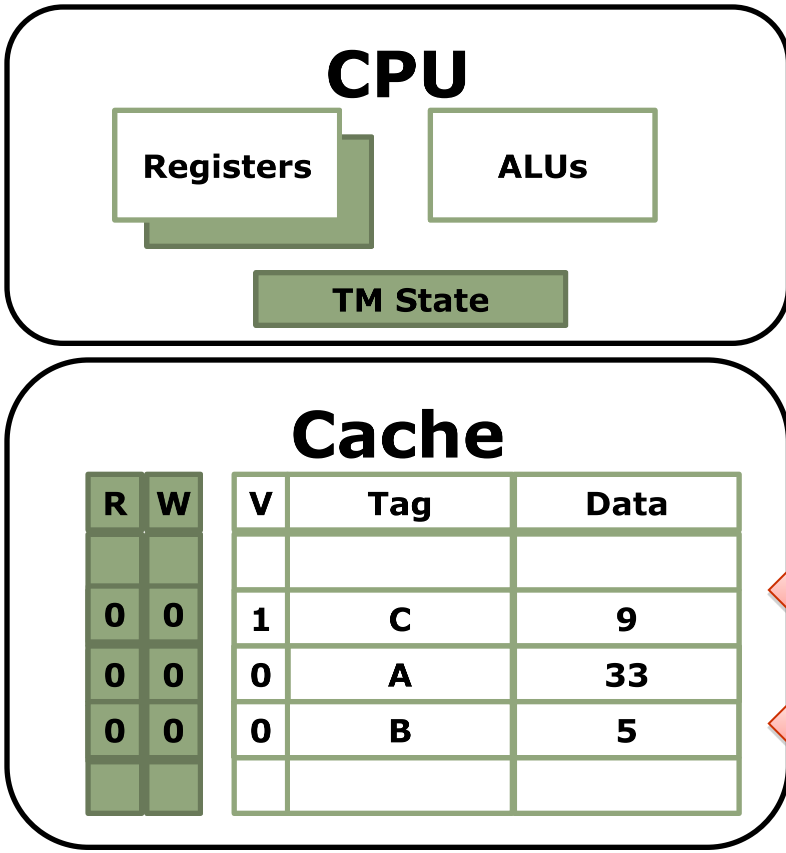


upgradeX B

```
Xbegin
    Load A
    Store B ⇐ 5
    Load C
Xcommit ⇦
```

- Fast 2-phase commit:
  1. Validate: Request exclusive access to write-set lines (if needed)
  2. Commit: Gang-reset R&W bits, turns write-set data to valid (dirty) data

HTM Conflict Detection




```
Xbegin
    Load A
    Store B ⇐ 5
    Load C ⇦
Xcommit
```

upgradeX D ☑

upgradeX A ☒

- Fast conflict detection & abort:
  - Check: Lookup exclusive requests in the read-set and write-set
  - Abort: Invalidate write-set, gang-reset R and W bits, restore checkpoint

HTM Advantages

- Fast common-case behavior
  - Zero-overhead tracking of read-set & write-set
  - Zero-overhead versioning
  - Fast commits & aborts without data movement
  - Continuous validation of read-set

- Strong isolation
  - Conflicts detected on non-transactional loads/stores as well

- Simplifies multi-core coherence and consistency [Hammond'04, Ceze'07]
  - Recall: Sequential consistency hard to implement
  - How would you enforce SC using HTM?

HTM Challenges

- Performance pathologies: How to handle frequent contention?
  - Should HTM guarantee fairness/enforce priorities?
- Size limitations: What happens if read-set + write-set exceed size of cache?
- Virtualization, I/O, syscalls…

- Hybrid TMs may get the best of both worlds:
  - Handle common case in HW, but with no guarantees
    - Abort on cache overflow, interrupt, syscall instruction, …
  - On abort, code can revert to software TM
  - Current approach in Intel's RTM…
  - … but still unclear how to integrate HTM & STM well

- Currently, slow/limited adoption by programmers, who must still support non-HTM systems