Lecture 20:
Transactional Memory

CMU 15-418: Parallel Computer Architecture and Programming (Spring 2012)

Giving credit

- **Many of the slides in today's talk are the work of Professor Christos Kozyrakis (Stanford University)**

Raising level of abstraction for synchronization

- Machine-level synchronization prims:
  - fetch-and-op, test-and-set, compare-and-swap

- We used these primitives to construct higher level, but still quite basic, synchronization prims:
  - lock, unlock, barrier

- Today:
  - transactional memory: higher level synchronization

What you should know

- What a transaction is
- The difference between the atomic construct and locks
- Design space of transactional memory implementations
    - data versioning policy
    - conflict detection policy
    - granularity of detection
- Understand HW implementation of transaction memory (consider how it relates to coherence protocol implementations we've discussed in the past)

Example

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

- Deposit is a read-modify-write operation: want "deposit" to be atomic with respect to other bank operations on this account.
- Lock/unlock pair is one mechanism to ensure atomicity (ensures mutual exclusion on the account)

Programming with transactional memory

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

```
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 explicit declaration or management of locks

- System implements synchronization
  - Typically with optimistic concurrency
  - Slow down only on true conflicts (R-W or W-W)

Declarative vs. imperative abstractions

- Declarative: programmer defines what should be done
  - Process all these 1000 tasks
  - Perform this set of operations atomically

- Imperative: programmer states how it should be done
  - Spawn N worker threads. Pull work from shared task queue
  - Acquire a lock, perform operations, release the lock

Transactional Memory (TM)

- Memory transaction
  - 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 though

Advantages of transactional memory

Another example: Java 1.4 HashMap

- Map: Key → Value

```
public Object get(Object key)  {
    int idx = hash(key);          // Compute hash
    HashEntry e = buckets[idx];   // to find bucket
    while (e != null)  {          // Find element in bucket
        if (equals(key, e.key))
              return e.value;
        e = e.next;
      }
    return null;
  }
```

- Not thread safe
- But no lock overhead when not needed

Synchronized HashMap

- Java 1.4 solution: synchronized layer
  - Convert any map to thread-safe variant
  - Uses explicit, coarse-grain locking specified by programmer

```
public Object get(Object key) {
    synchronized (mutex) {  // mutex guards all accesses to hashMap
            return myHashMap.get(key);
      }
  }
```

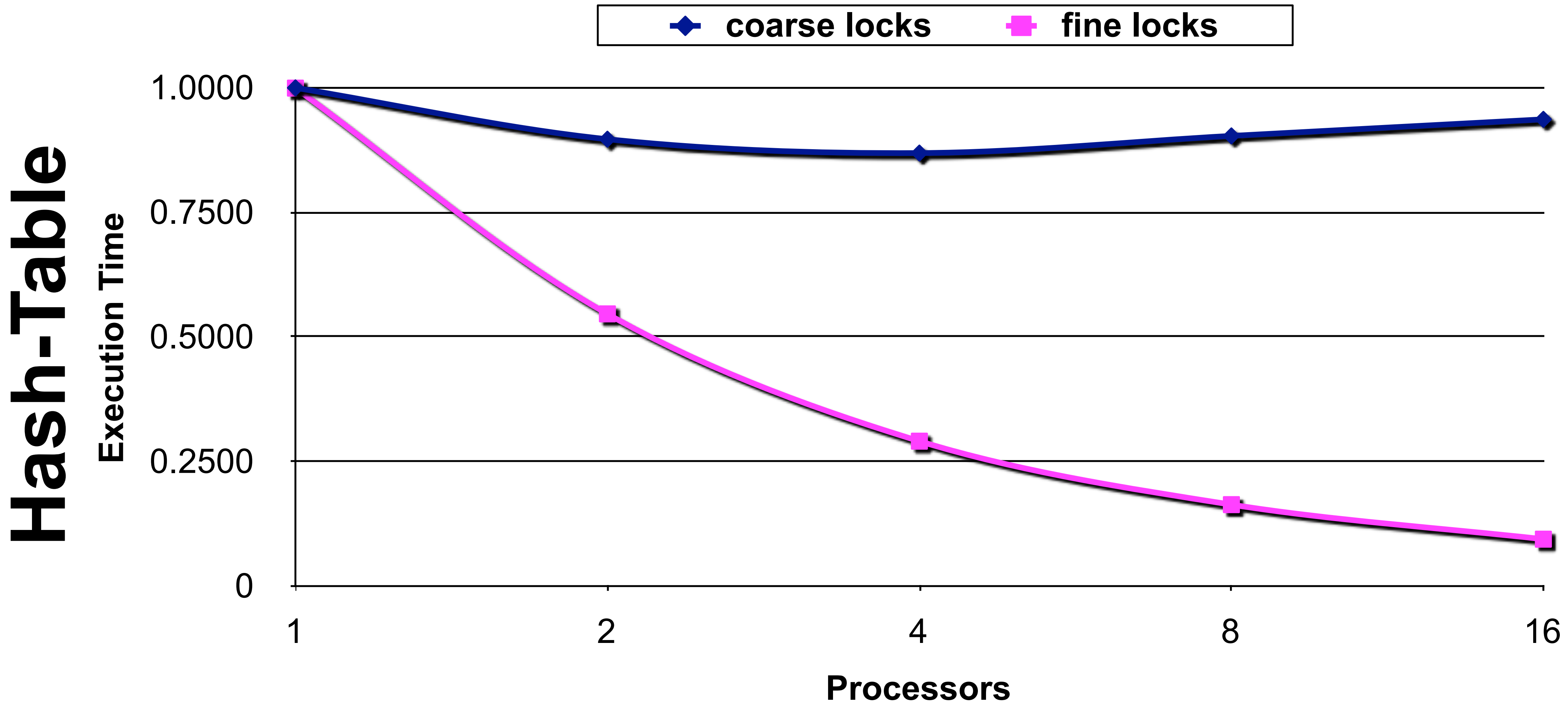
- Coarse-grain synchronized HashMap
  - Pros: thread-safe, easy to program
  - Cons: limits concurrency, poor scalability
    - Only one thread can operate on map at any time

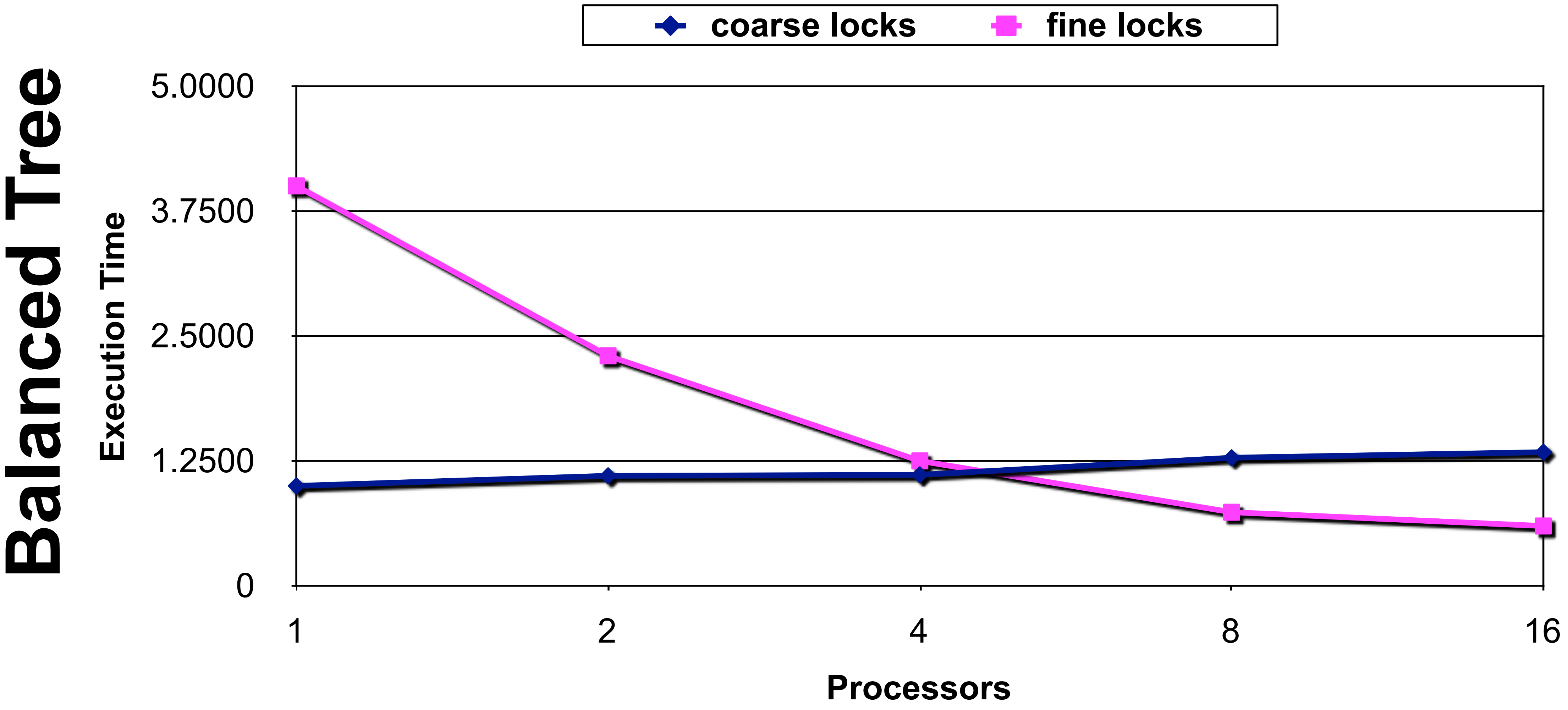
Better solution?

```
public Object get(Object key)  {
    int idx = hash(key);                  // Compute hash
    HashEntry e = buckets[idx];           // to find bucket
    while (e != null)  {                  // Find element in bucket
        if (equals(key, e.key))
               return e.value;
        e = e.next;
      }
    return null;
  }
```

- **Fined-grained synchronization: e.g., lock per bucket**
- **Now thread safe: but lock overhead even if not needed**

Performance: Locks





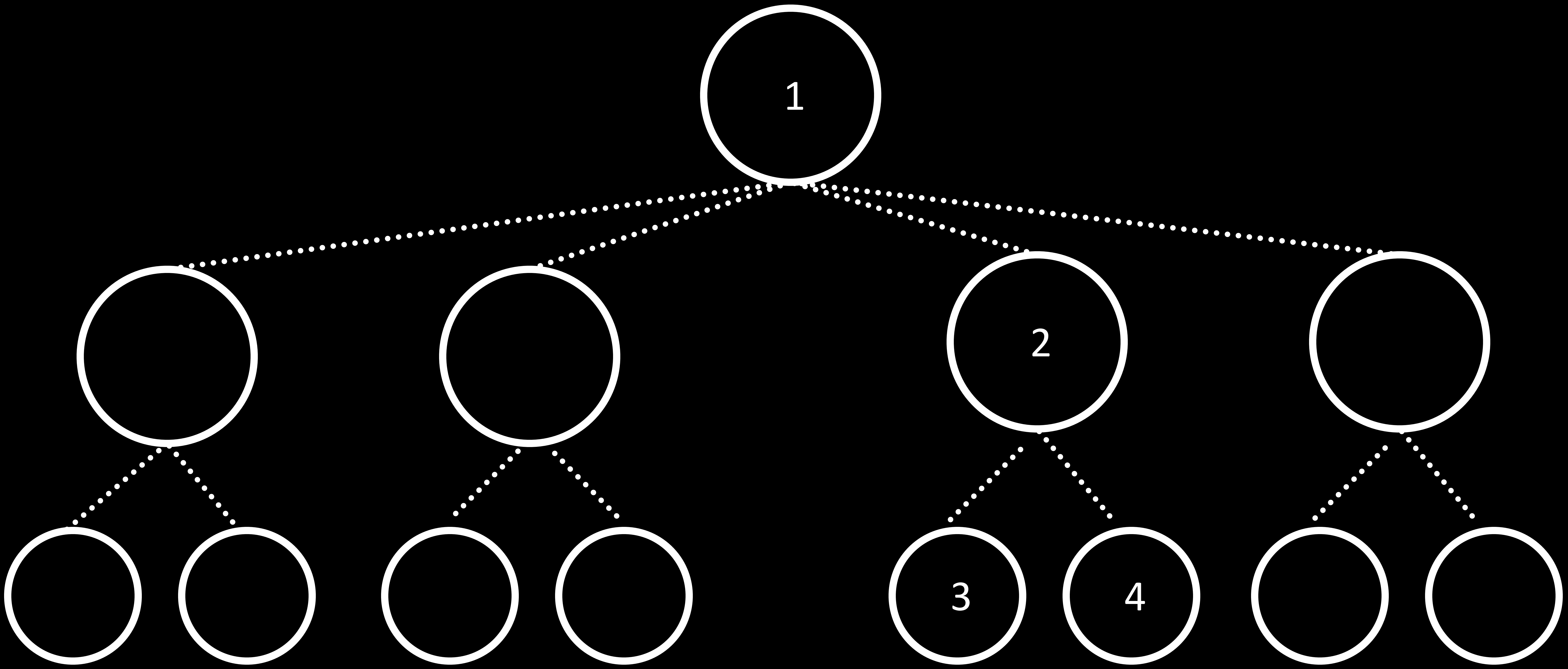
Transactional HashMap

- Simply enclose all operation in atomic block
  - System ensures atomicity

```
public Object get(Object key) {
      atomic {               // System guarantees atomicity
        return m.get(key);
      }
 }
```

- Transactional HashMap
  - Pros: thread-safe, easy to program
  - Q: good performance & scalability?
    - Depends on the implementation, but typically yes

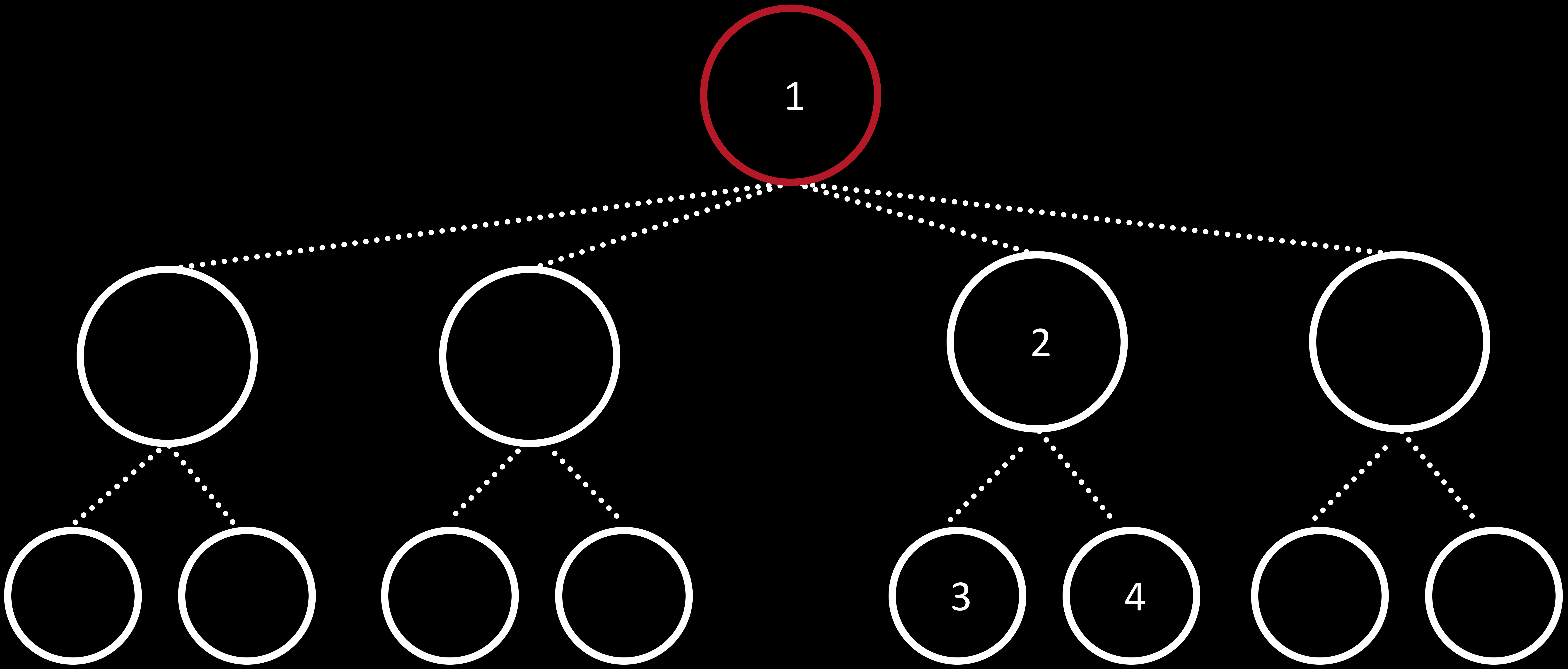
Another example: tree update



Goal: Modify node 3 in a thread-safe way.

Slide credit: Austen McDonald

Synchronization Example



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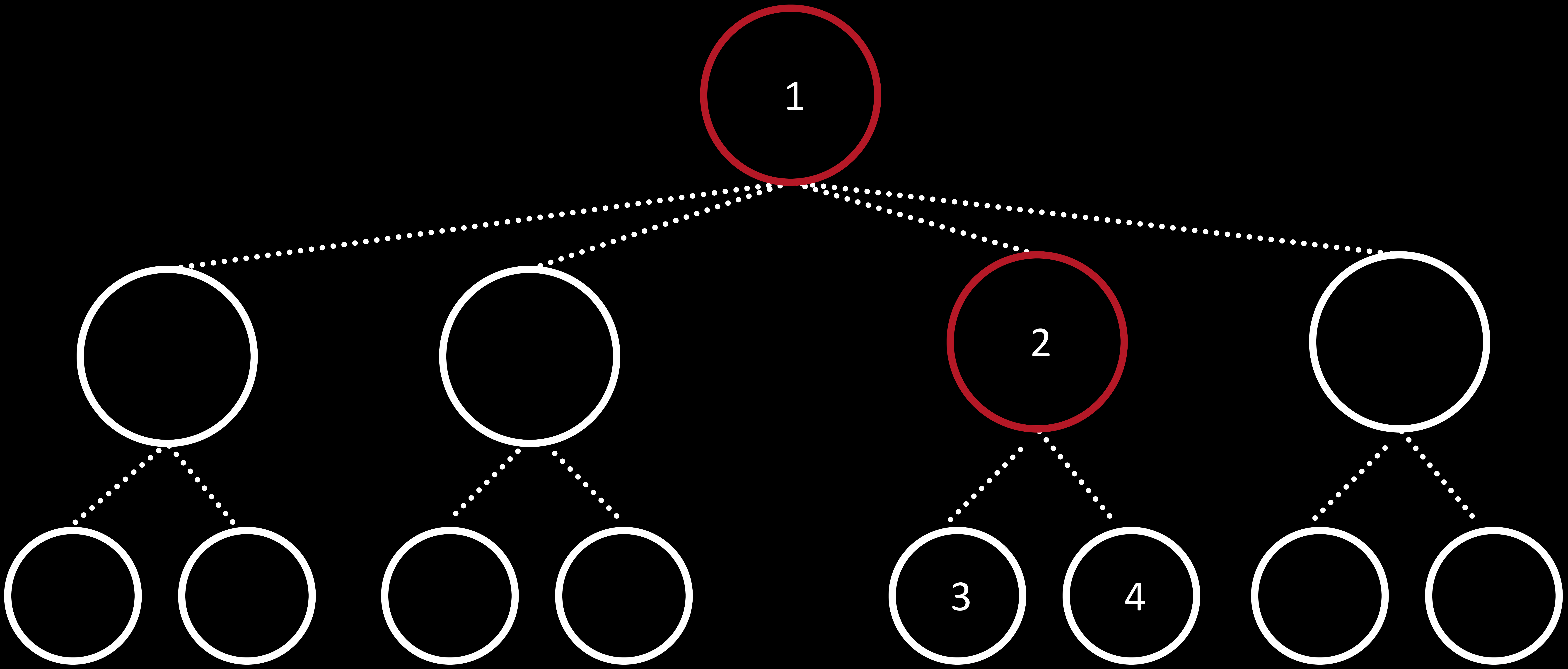
Synchronization Example



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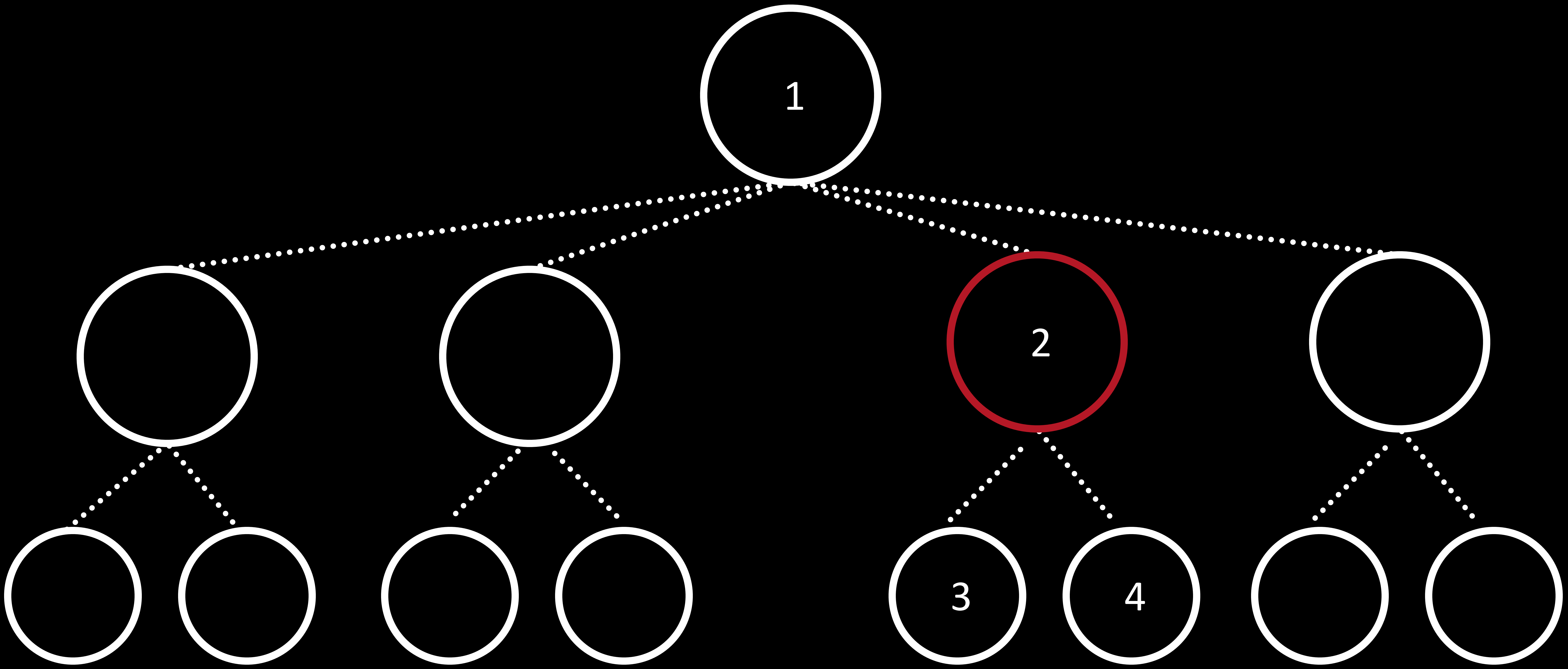
Synchronization Example



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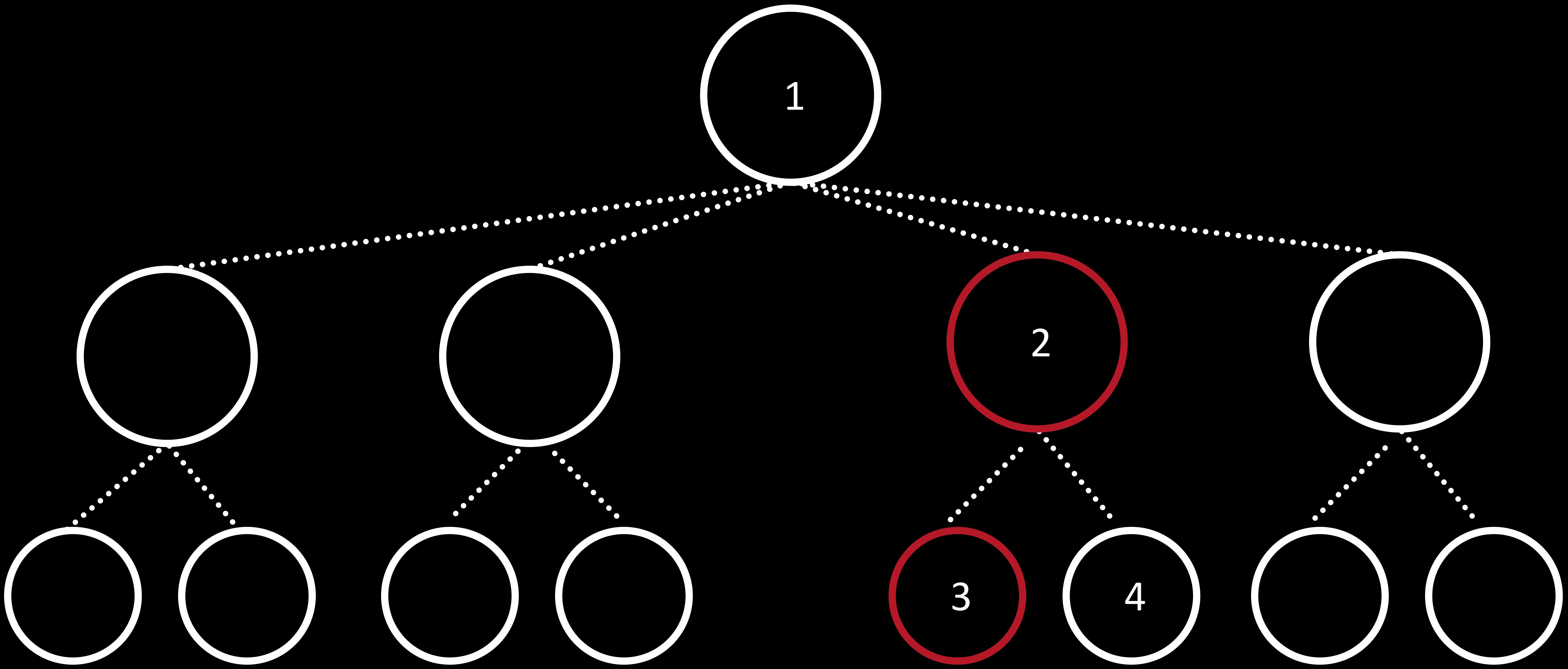
Synchronization Example



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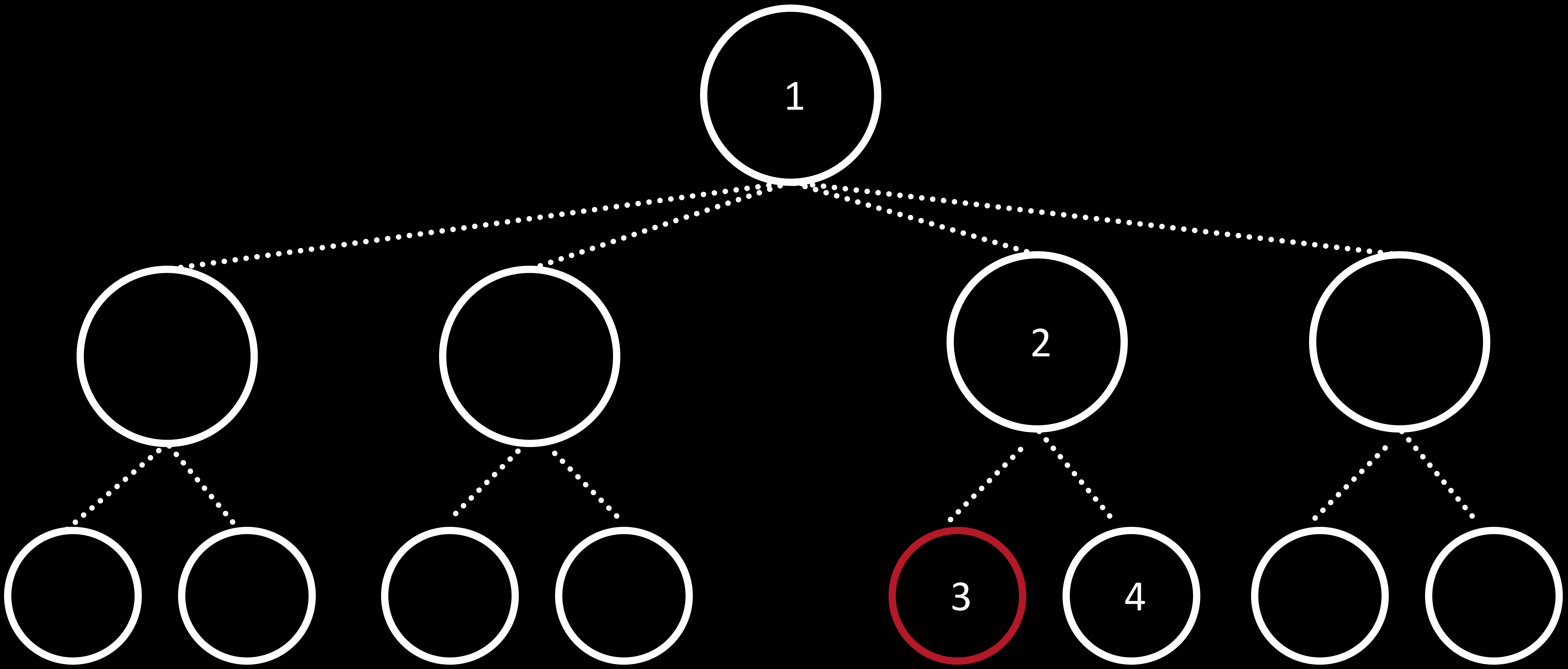
Synchronization Example



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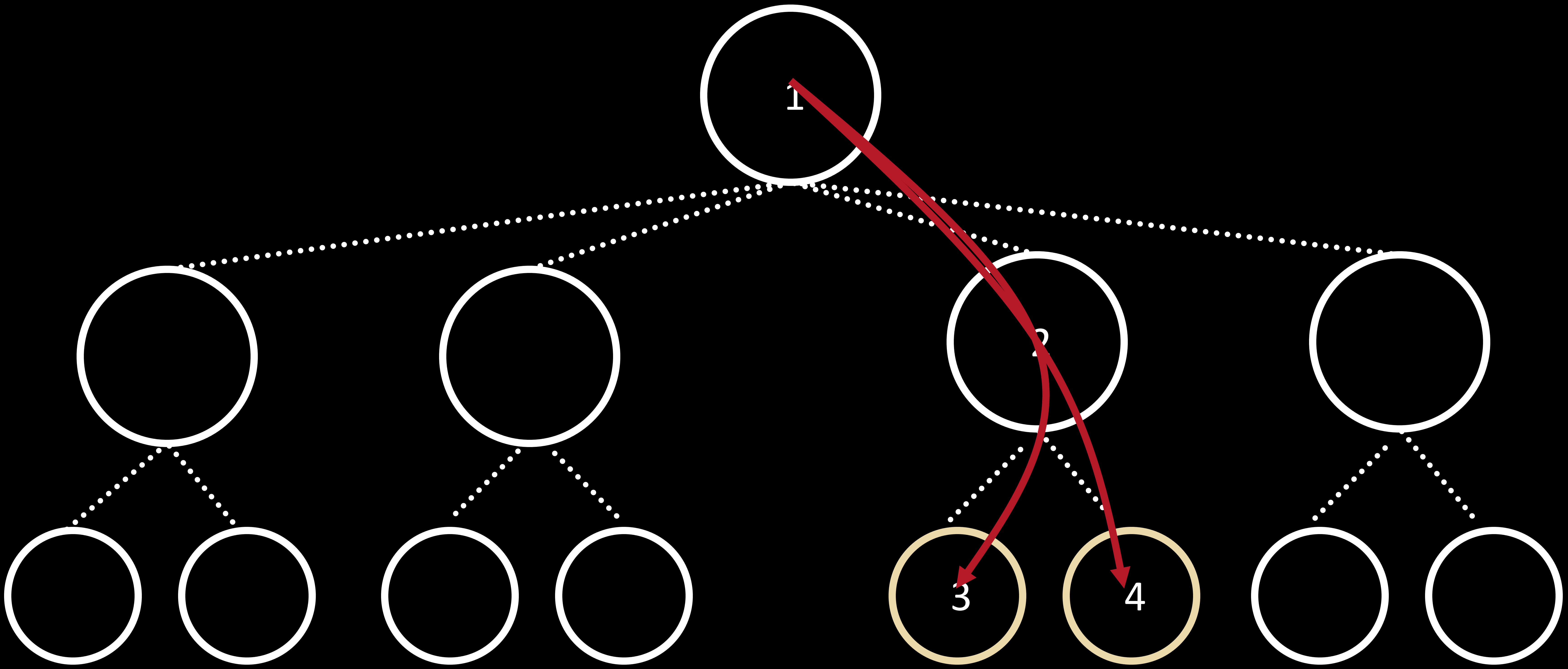
Synchronization Example



Goals: Modify nodes **3 and 4** in a thread-safe way.

Locking prevents concurrency

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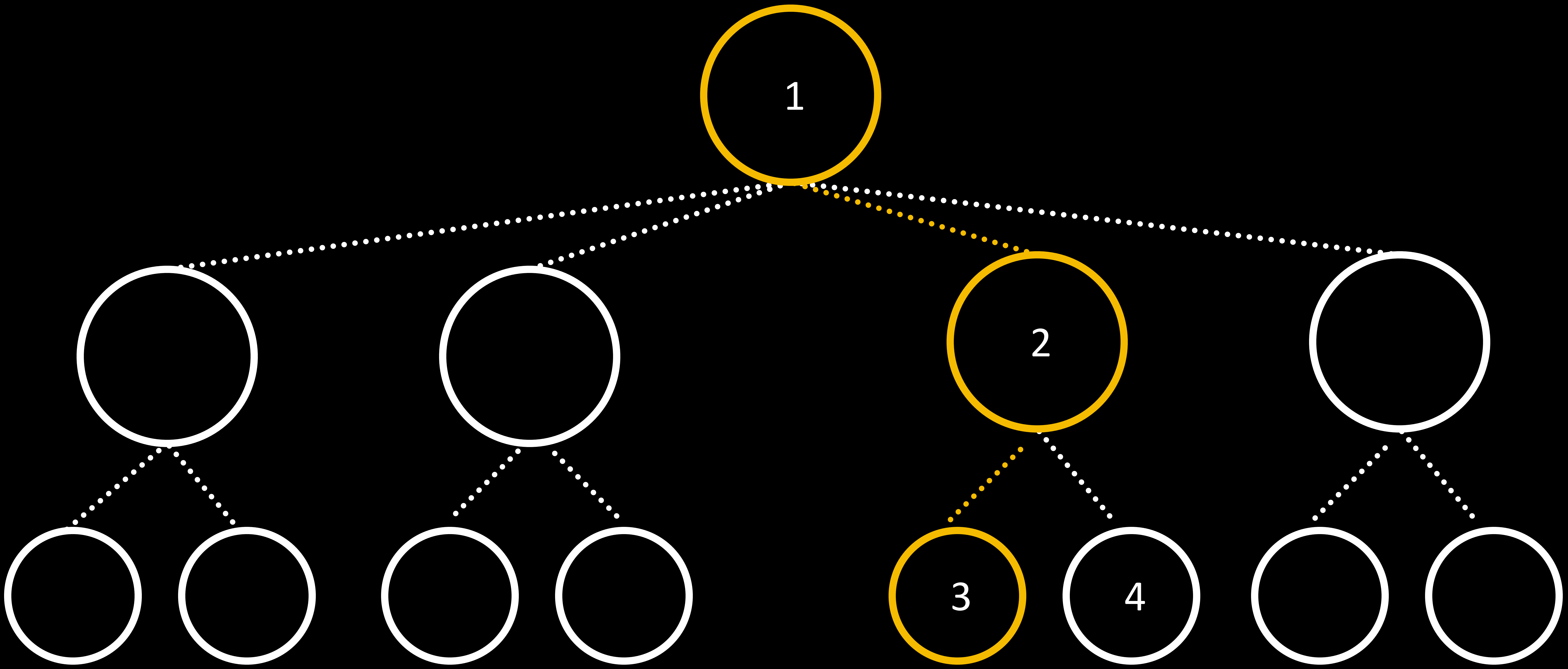
TM Example



Transaction A

READ: 1, 2, 3

WRITE:

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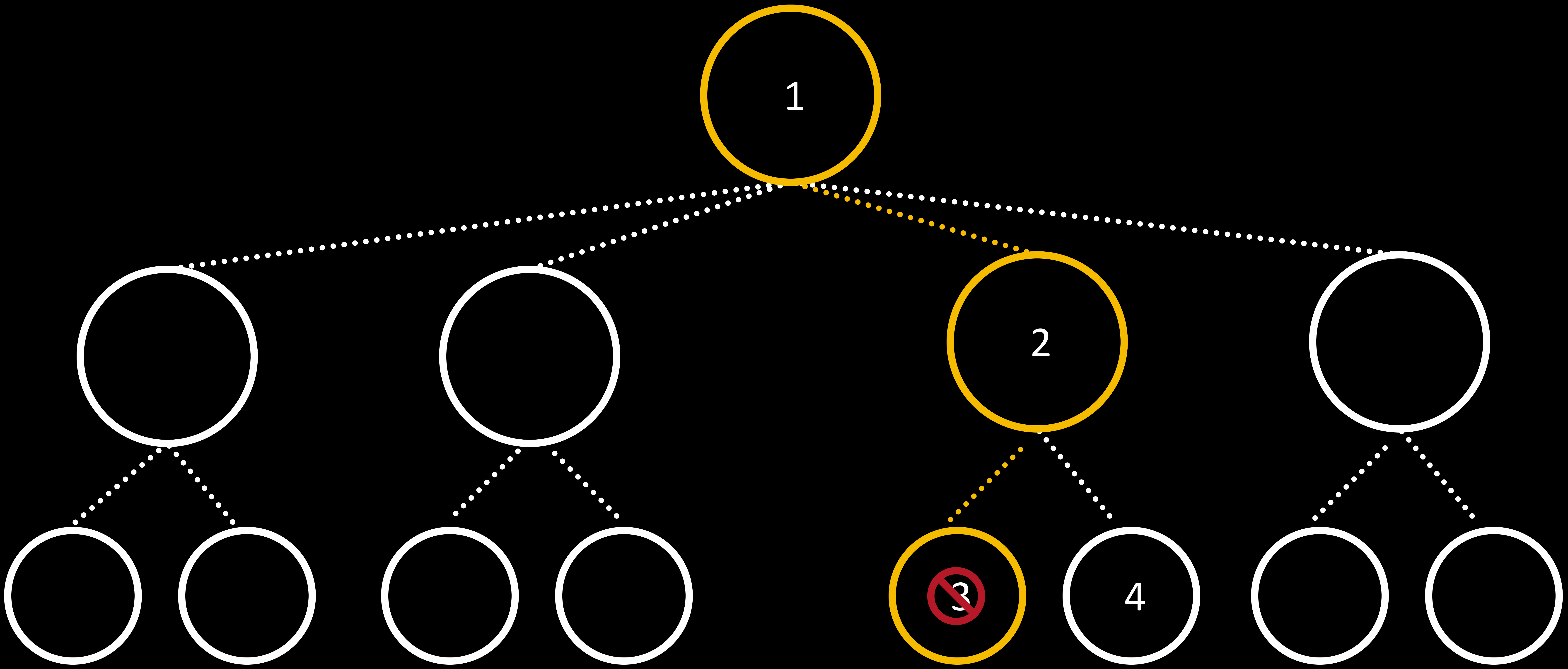
TM Example



Transaction A

READ: 1, 2, 3

WRITE: 3

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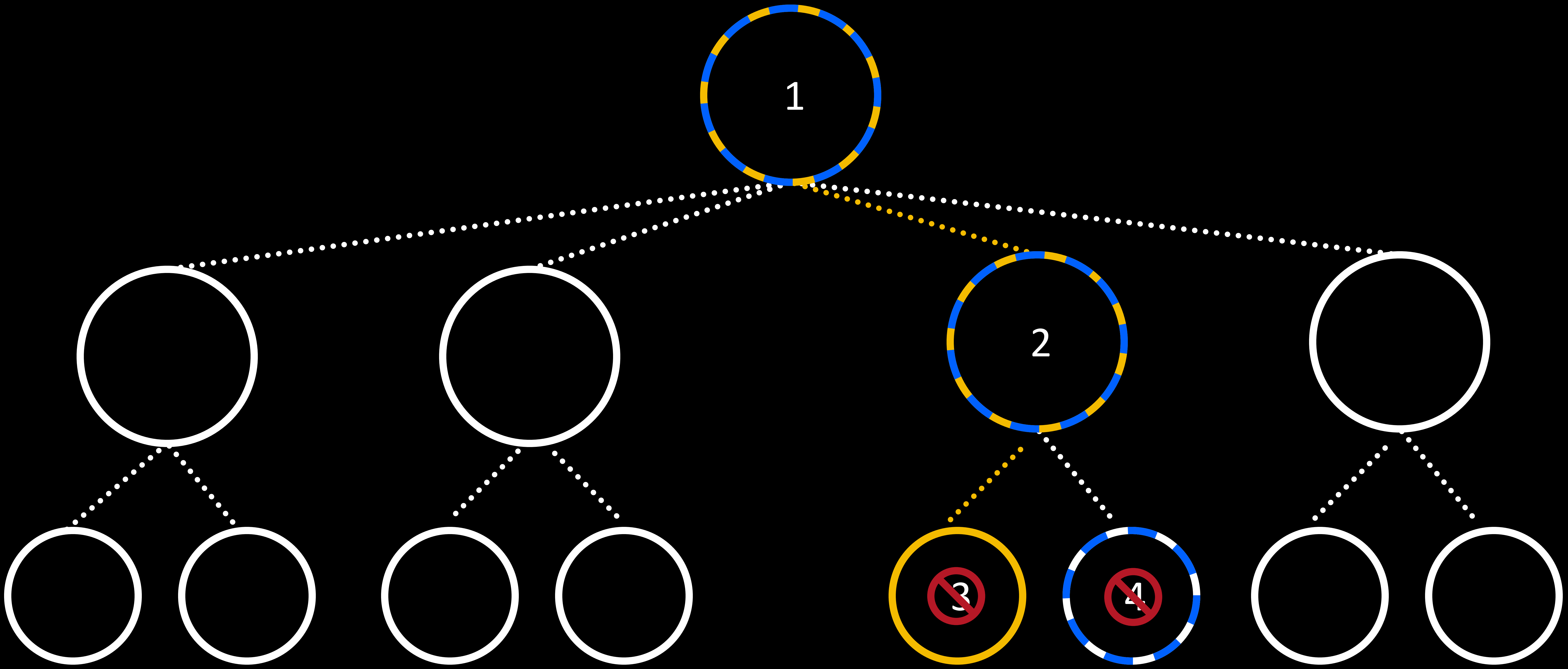
TM Example: no conflicts



Transaction A
READ: 1, 2, 3
WRITE: 3

Transaction B
READ: 1, 2, 4
WRITE: 4

NO READ-WRITE, or WRITE-WRITE conflicts!

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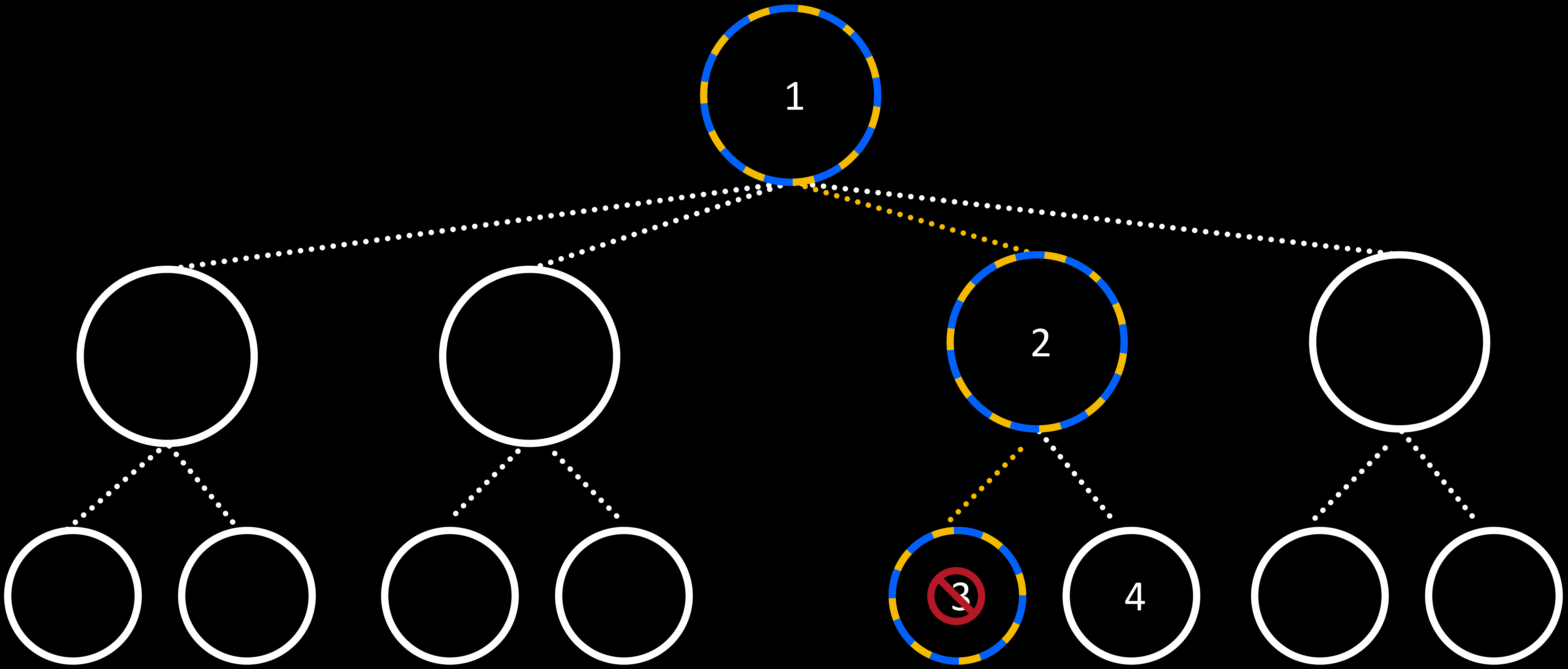
TM Example: with conflicts



Transaction A
READ: 1, 2, 3
WRITE: 3

Transaction B
READ: 1, 2, 3
WRITE: 3

Conflicts exist! Must be serialized!

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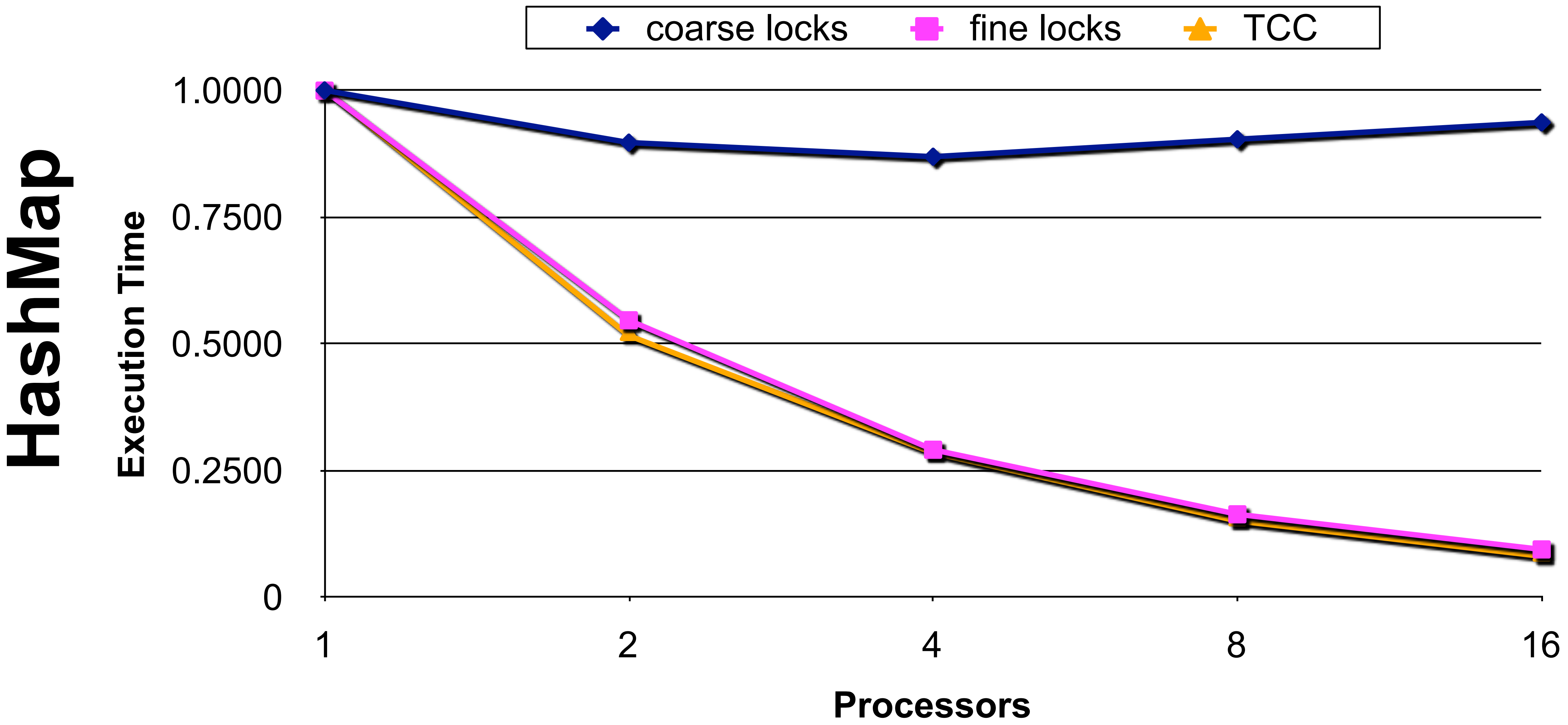
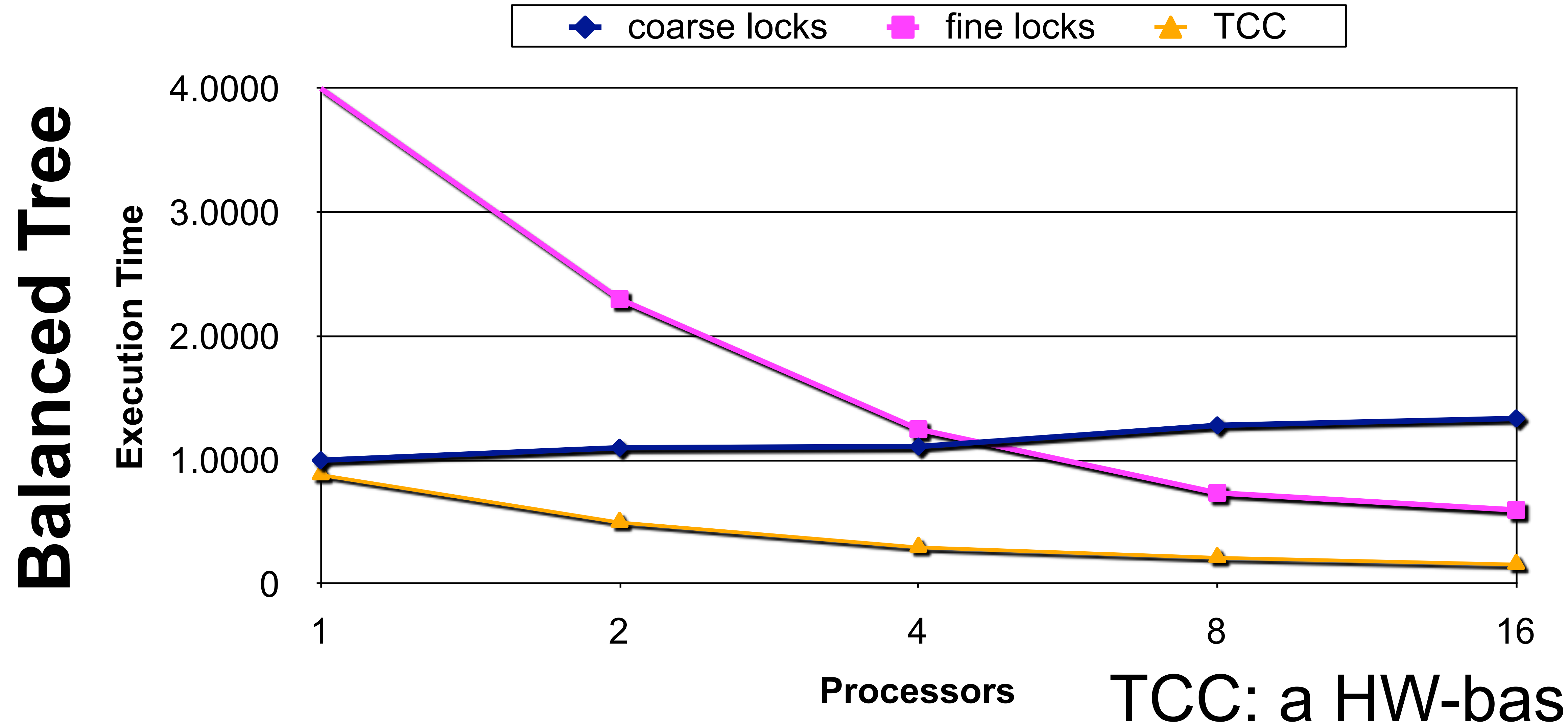
Performance: locks vs. transactions





TCC: a HW-based TM system

Failure atomicity: locks

```
void transfer(A, B, amount)
   synchronized(bank) {
      try {
        withdraw(A, amount);
        deposit(B, amount);
      }
      catch(exception1) { /* undo code 1*/ }
      catch(exception2) { /* undo code 2*/ }
    …
   }
```

- Manually catch exceptions
  - Programmer provides undo code on a case by case basis
    - Complexity: what to undo and how…
  - Some side-effects may become visible to other threads
    - E.g., an uncaught case can deadlock the system…

Failure atomicity: transactions

```
void transfer(A, B, amount)
   atomic {
      withdraw(A, amount);
      deposit(B, amount);
   }
```

- System processes exceptions
  - All but those explicitly managed by the programmer
  - Transaction is aborted and updates are undone
  - No partial updates are visible to other threads
    - E.g., No locks held by a failing threads…

Composability: locks

```
void transfer(A, B, amount)
   synchronized(A) {
   synchronized(B) {
        withdraw(A, amount);
        deposit(B, amount);
   }
   }
```

```
void transfer(B, A, amount)
   synchronized(B) {
   synchronized(A) {
        withdraw(B, amount);
        deposit(A, amount);
   }
   }
```

- Composing lock-based code can be tricky
  - Requires system-wide policies to get correct
  - Breaks software modularity

- Between an extra lock & a hard place
  - Fine-grain locking: good for performance, but can lead to deadlock

Composability: transactions

```
void transfer(A, B, amount)
   atomic {
      withdraw(A, amount);
      deposit(B, amount);
   }
```

```
void transfer(B, A, amount)
   atomic {
      withdraw(B, amount);
      deposit(A, amount);
   }
```

- Transactions compose gracefully
  - Programmer declares global intent (atomic transfer)
    - No need to know of global implementation strategy
  - Transaction in transfer subsumes those in withdraw & deposit
    - Outermost transaction defines atomicity boundary

- System manages concurrency as well as possible
  - Serialization for transfer(A, B, $100) & transfer(B, A, $200)
  - Concurrency for transfer(A, B, $100) & transfer(C, D, $200)

Advantages of transactional memory

- Easy to use synchronization construct
  - As easy to use as coarse-grain locks
  - Programmer declares, system implements
- Often performs as well as fine-grain locks
  - Automatic read-read concurrency & fine-grain concurrency
- Failure atomicity & recovery
  - No lost locks when a thread fails
  - Failure recovery = transaction abort + restart
- Composability
  - Safe & scalable composition of software modules

Example integration with OpenMP

- Example: OpenTM = OpenMP + TM
  - OpenMP: master-slave parallel model
    - Easy to specify parallel loops & tasks
  - TM: atomic & isolation execution
    - Easy to specify synchronization and speculation

- OpenTM features
  - Transactions, transactional loops & sections
  - Data directives for TM (e.g., thread private data)
  - Runtime system hints for TM

- Code example

```
#pragma omp transfor schedule (static, chunk=50)
  for (int i=0; i<N; i++) {
     bin[A[i]] = bin[A[i]]+1;
   }
```

Atomic() ≠ lock()+unlock()

- The difference
  - Atomic: high-level declaration of atomicity
    - Does not specify implementation/blocking behavior
    - Does not provide a consistency model
  - Lock: low-level blocking primitive
    - Does not provide atomicity or isolation on its own

- Keep in mind
  - Locks can be used to implement atomic(), but…
  - Locks can be used for purposes beyond atomicity
    - Cannot replace all lock regions with atomic regions
  - Atomic eliminates many data races, but..
  - Programming with atomic blocks can still suffer from atomicity violations. e.g., atomic sequence incorrectly split into two atomic blocks

Example: lock-based code that does not work with atomic

```
// Thread 1
synchronized(lock1) {
  …
  flagB = true;
  while (flagA==0);
  …
}
```

```
// Thread 2
synchronized(lock2) {
  …
  flagA = true;
  while (flagB==0);
  …
}
```

- What is the problem with replacing synchronized with atomic?

Example: atomicity violation

```
// Thread 1
atomic() {
  …
  ptr = A;
  …
}

atomic() {
  B = ptr->field;
}
```

```
// Thread 2
atomic {
  …
  ptr = NULL;
}
```

- Programmer mistake: logically atomic code sequence separated into two atomic() blocks.

Transactional memory: summary + benefits

- TM = declarative synchronization
  - User specifies requirement (atomicity & isolation)
  - System implements in best possible way

- Motivation for TM
  - Difficult for user to get explicit sync right
    - Correctness vs. performance vs. complexity
  - Explicit sync is difficult to scale
    - Locking scheme for 4 CPUs is not the best for 64
  - Difficult to do explicit sync with composable SW
    - Need a global locking strategy
  - Other advantages: fault atomicity, …

- Productivity argument: system support for transactions can achieve 90% of the benefit of programming with fined-grained locks, with 10% of the development time

Implementing transactional memory

Recall: transactional memory

- 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 though

TM implementation basics

- TM systems must provide atomicity and isolation
  - Without sacrificing concurrency

- Basic implementation requirements
  - Data versioning (ALLOWS abort)
  - Conflict detection & resolution (WHEN to abort)

- Implementation options
  - Hardware transactional memory (HTM)
  - Software transactional memory (STM)
  - Hybrid transactional memory
    - e.g., Hardware accelerated STMs

Data versioning

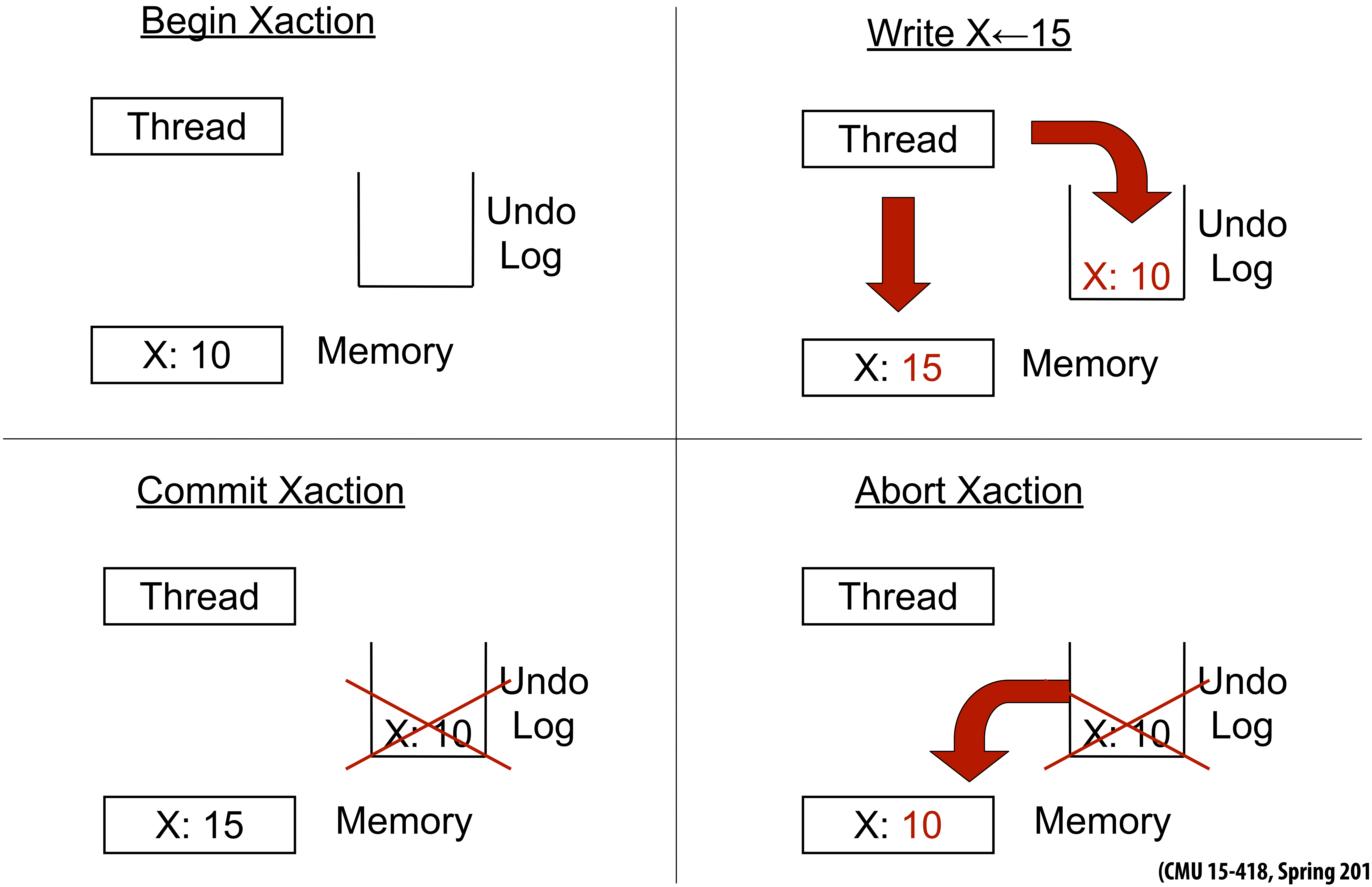
- Manage uncommited (new) and commited (old) versions of data for concurrent transactions

1. Eager versioning (undo-log based)

2. Lazy versioning (write-buffer based)

Eager versioning

Update memory immediately, maintain “undo log” in case of abort



Begin Xaction

Thread

Undo Log

X: 10

Memory

Write X←15

Thread

Undo Log

X: 10

X: 15

Memory

Commit Xaction

Thread

~~X: 10~~

Undo Log

X: 15

Memory

Abort Xaction

Thread

~~X: 10~~

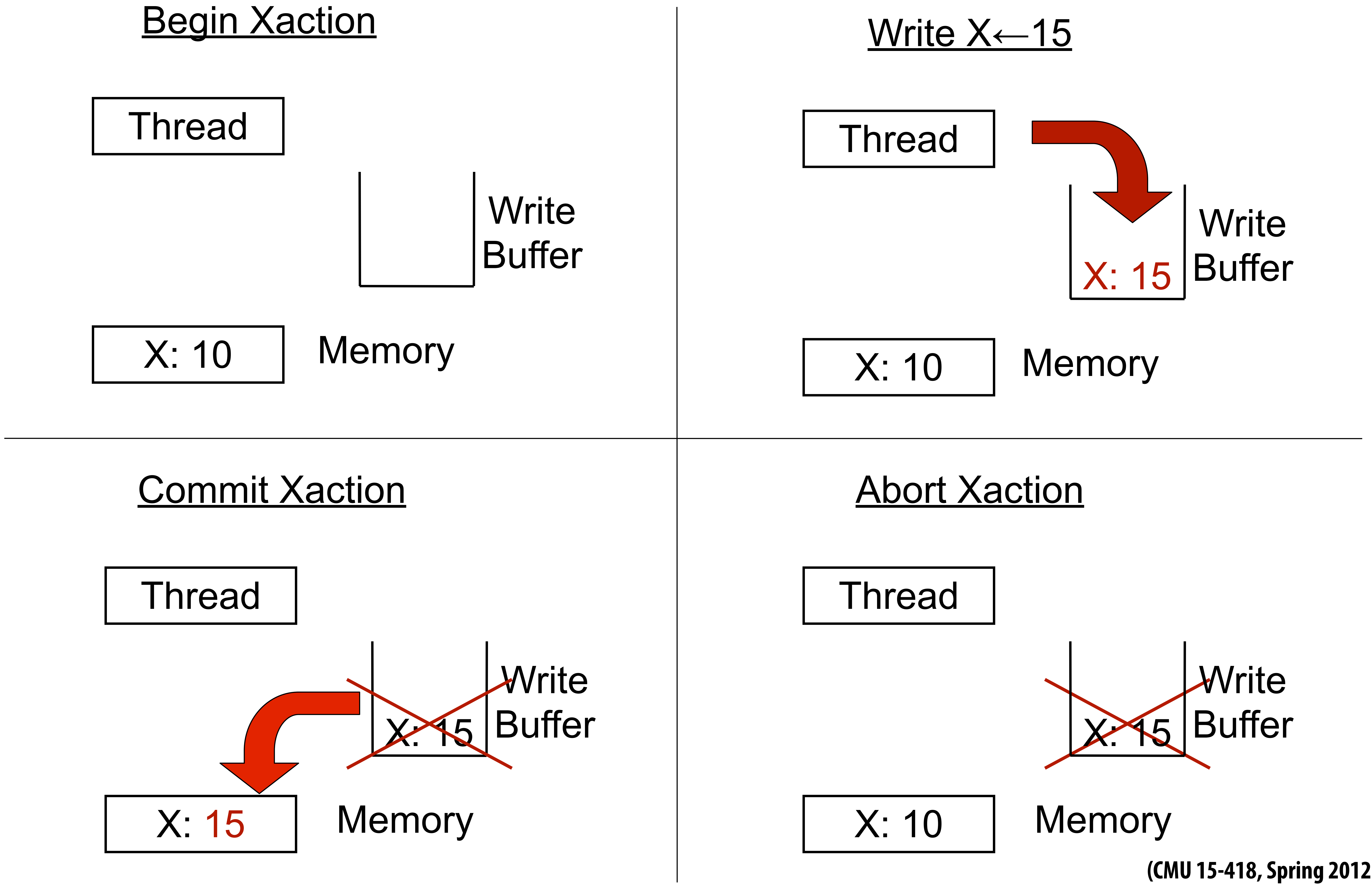
Undo Log

X: 10

Memory

Lazy versioning

Log memory updates in transaction write buffer, flush buffer on commit



Begin Xaction

Thread

Write Buffer

X: 10

Memory

Write X←15

Thread

X: 15

Write Buffer

X: 10

Memory

Commit Xaction

Thread

~~X: 15~~

Write Buffer

X: 15

Memory

Abort Xaction

Thread

~~X: 15~~

Write Buffer

X: 10

Memory

Data versioning

- Manage uncommited (new) and commited (old) versions of data for concurrent transactions

1. Eager versioning (undo-log based)
    - Update memory location directly
    - Maintain undo info in a log (per store penalty)
    - \+ Faster commit
    - – Slower aborts, fault tolerance issues (crash in middle of trans)

2. Lazy versioning (write-buffer based)
    - Buffer data until commit in a write-buffer
    - Update actual memory location on commit
    - \+ Faster abort, no fault tolerance issues
    - – Slower commits

Conflict detection

- Detect and handle conflicts between transactions
  - read-write conflict: transaction A reads addr X, which was written to by pending transaction B
  - write-write conflict: transactions A and B are pending, both write to address X.

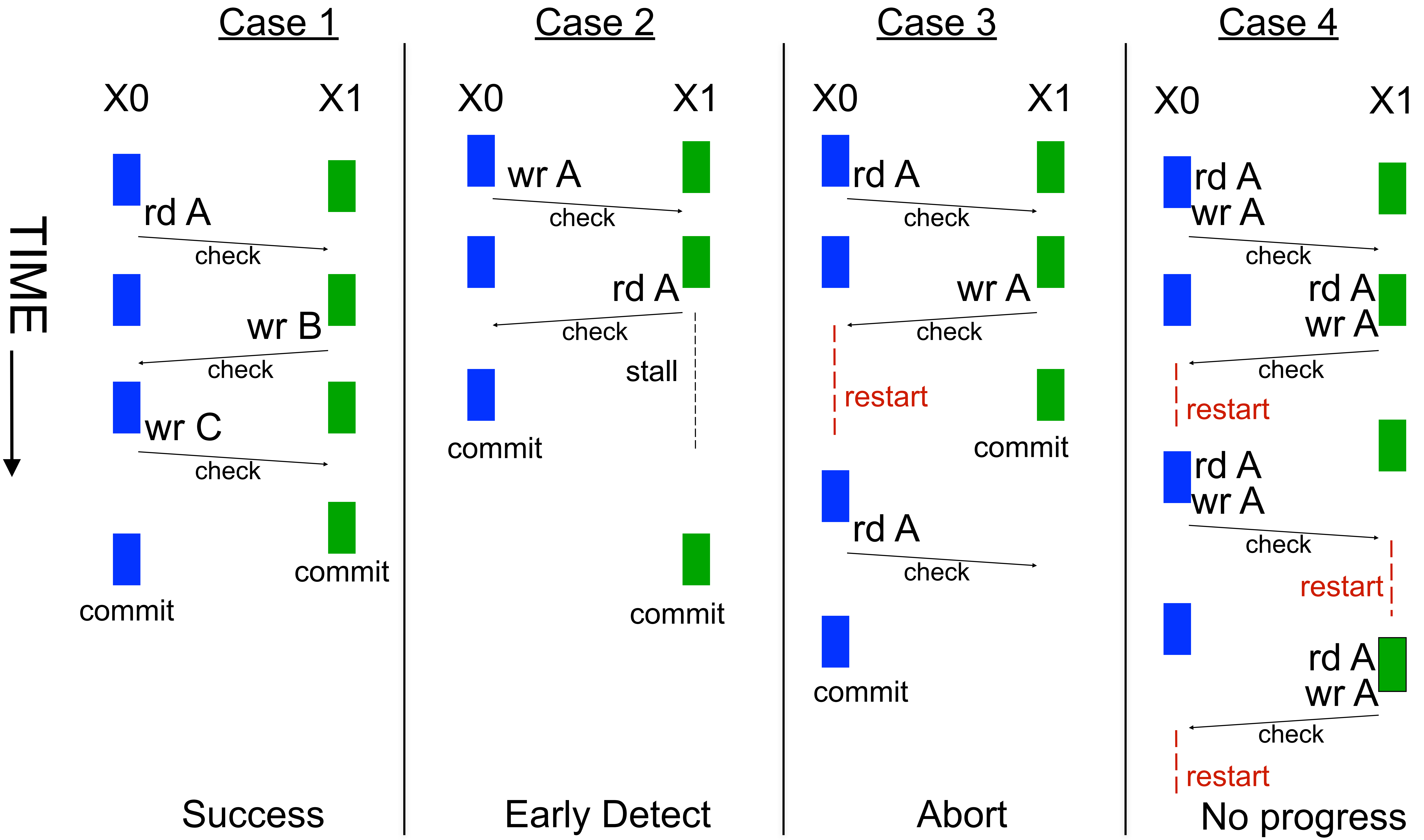
  - Must track the transaction's read-set and write-set
    - Read-set: addresses read within the transaction
    - Write-set: addresses written within transaction

Pessimistic detection

- Check for conflicts during loads or stores
  - e.g., HW implementation will check through coherence actions (will discuss later)

- “Contention manager” decides to stall or abort transaction
  - Various priority policies to handle common case fast

Pessimistic detection example



TIME

Case 1

X0 X1

rd A

check

wr B

check

wr C

check

commit

commit

Success

Case 2

X0 X1

wr A

check

rd A

check

stall

commit

commit

Early Detect

Case 3

X0 X1

rd A

check

wr A

check

restart

commit

rd A

check

commit

Abort

Case 4

X0 X1

rd A
wr A

check

rd A
wr A

check

restart

rd A
wr A

check

restart

rd A
wr A

check

restart

No progress

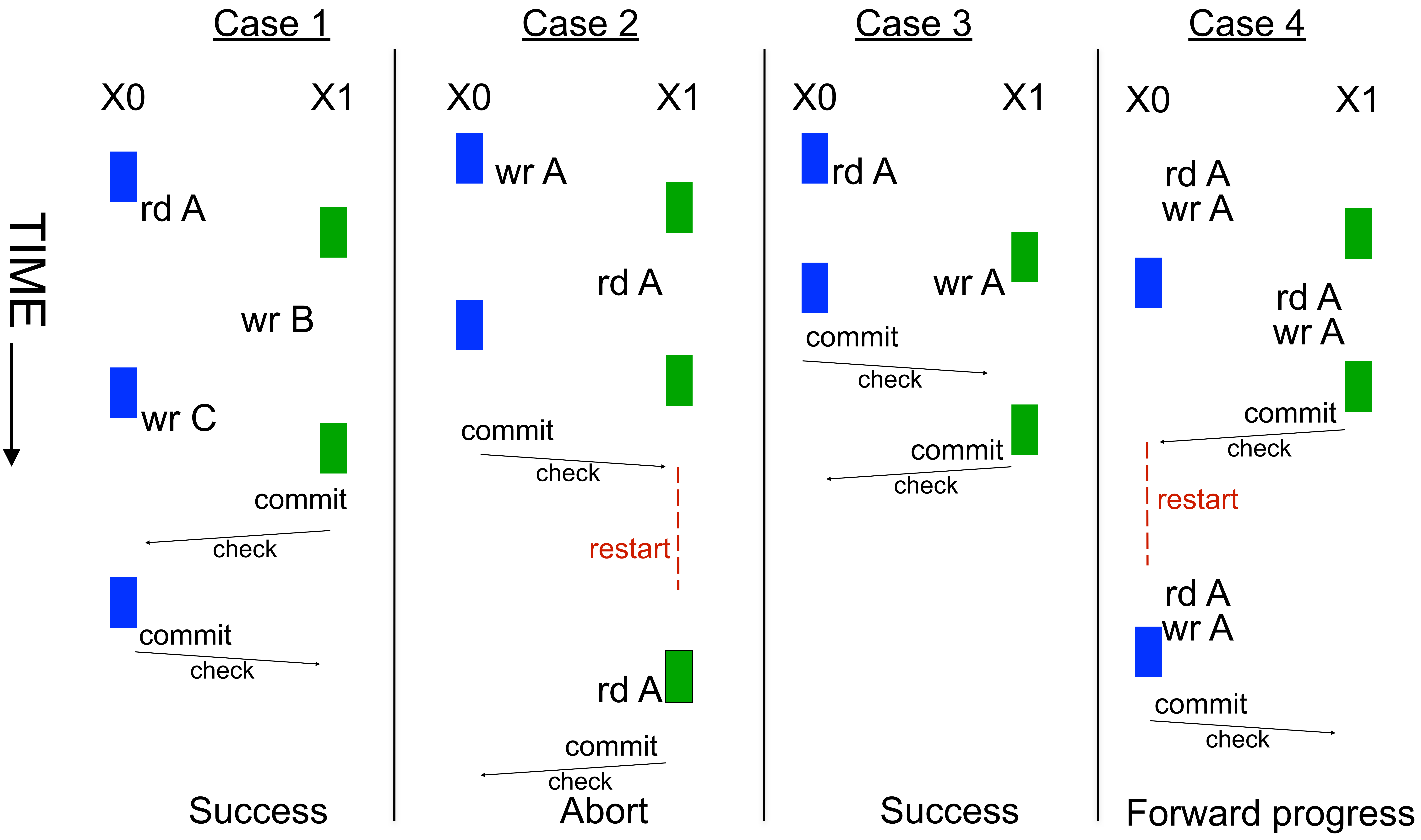
Optimistic detection

- Detect conflicts when a transaction attempts to commit
  - 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: can use optimistic & pessimistic schemes together
  - Several STM systems use optimistic for reads and pessimistic for writes

Optimistic detection



TIME

Case 1

X0 X1

rd A

wr B

wr C

commit

check

commit

check

Success

Case 2

X0 X1

wr A

rd A

commit

check

restart

rd A

commit

check

Abort

Case 3

X0 X1

rd A

wr A

commit

check

commit

check

Success

Case 4

X0 X1

rd A
wr A

rd A
wr A

commit

check

restart

rd A
wr A

commit

check

Forward progress

Conflict detection trade-offs

1. Pessimistic conflict detection (a.k.a. “encounter” or “eager”)
   - \+ Detect conflicts early
     - Undo less work, turn some aborts to stalls
   - – No forward progress guarantees, more aborts in some cases
   - – Fine-grain communication
   - – On critical path

2. Optimistic conflict detection (a.k.a. “commit” or “lazy”)
   - \+ Forward progress guarantees
   - \+ Potentially less conflicts, bulk communication
   - – Detects conflicts late, can still have fairness problems

Conflict detection granularity

- Object granularity (SW-based techniques)
  - + Reduced overhead (time/space)
  - + Close to programmer's reasoning
  - – False sharing on large objects (e.g. arrays)
- Word granularity
  - + Minimize false sharing
  - – Increased overhead (time/space)
- Cache line granularity
  - + Compromise between object & word

- Mix & match ➔ best of both words
  - Word-level for arrays, object-level for other data, …

TM implementation space (examples)

- Hardware TM systems
  - Lazy + optimistic: Stanford TCC
  - Lazy + pessimistic: MIT LTM, Intel VTM
  - Eager + pessimistic: Wisconsin LogTM
  - Eager + optimistic: not practical

- Software TM systems
  - Lazy + optimistic (rd/wr): Sun TL2
  - Lazy + optimistic (rd)/pessimistic (wr): MS OSTM
  - Eager + optimistic (rd)/pessimistic (wr): Intel STM
  - Eager + pessimistic (rd/wr): Intel STM

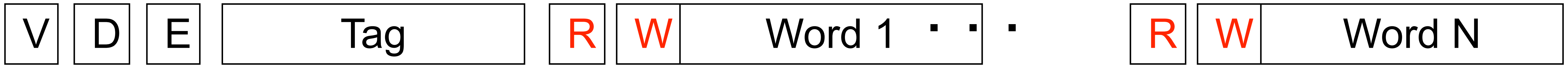
- Optimal design remains an open question
  - May be different for HW, SW, and hybrid

Hardware transactional memory (HTM)

- Data versioning in caches
  - Cache the write-buffer or the undo-log
  - New cache meta-data to track read-set and write-set
  - Can do with private, shared, and multi-level caches
- Conflict detection through cache coherence protocol
  - Coherence lookups detect conflicts between transactions
  - Works with snooping & directory coherence
- Notes
  - Register checkpoint must be taken at transaction begin

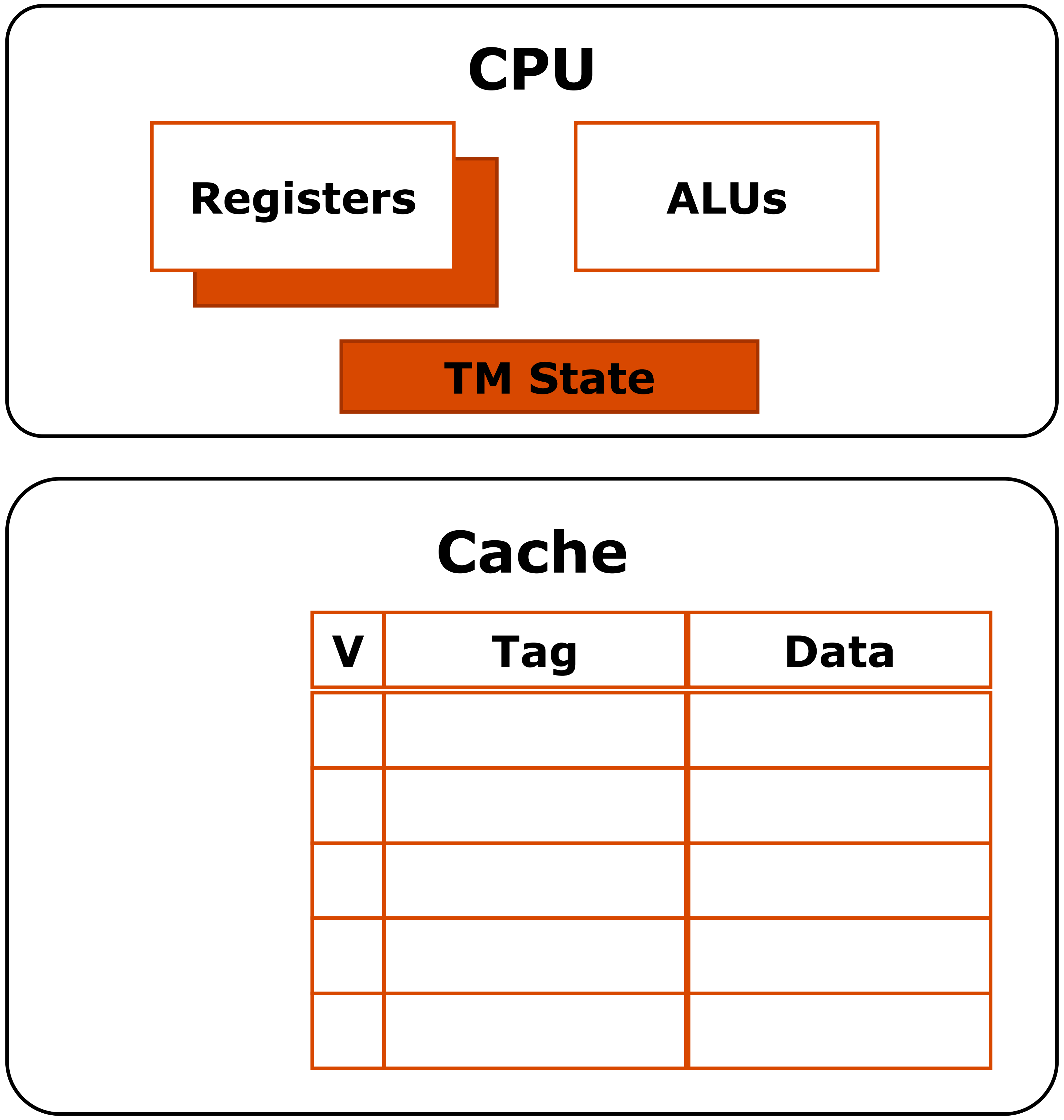
HTM design

- Cache lines annotated to track read-set & write set
  - R bit: indicates data read by transaction; set on loads
  - W bit: indicates data written by transaction; set on stores
    - R/W bits can be at word or cache-line granularity
  - R/W bits gang-cleared on transaction commit or abort
  - For eager versioning, need a 2nd cache write for undo log



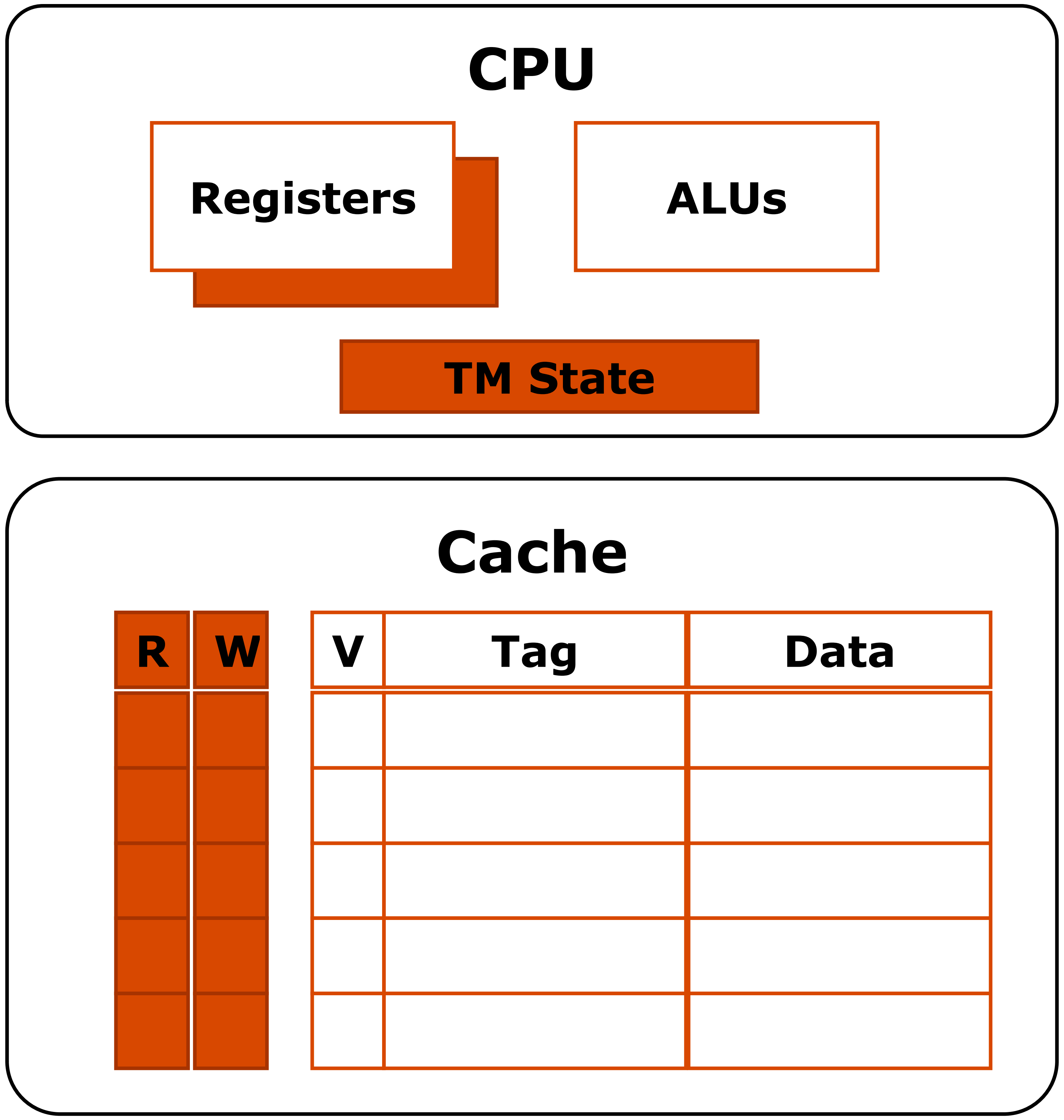
- Coherence requests check R/W bits to detect conflicts
  - Shared request to W-word is a read-write conflict
  - Exclusive request to R-word is a write-read conflict
  - Exclusive request to W-word is a write-write conflict

Example HTM: lazy optimistic



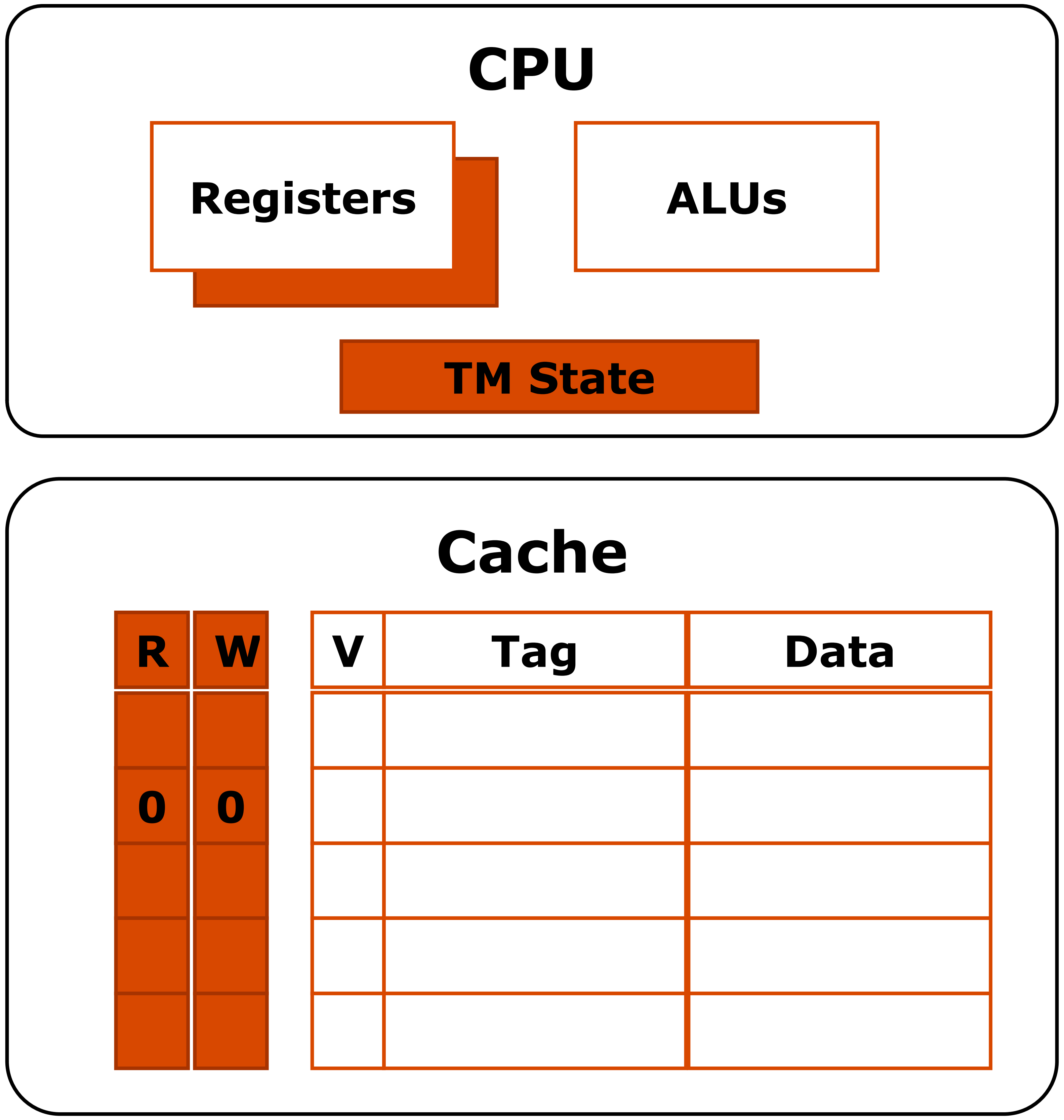
- CPU changes
  - Register checkpoint (available in many CPUs)
  - TM state registers (status, pointers to handlers, …)

Example HTM: Lazy Optimistic



- Cache changes
  - R bit indicates membership to read-set
  - W bit indicates membership to write-set

HTM transaction execution

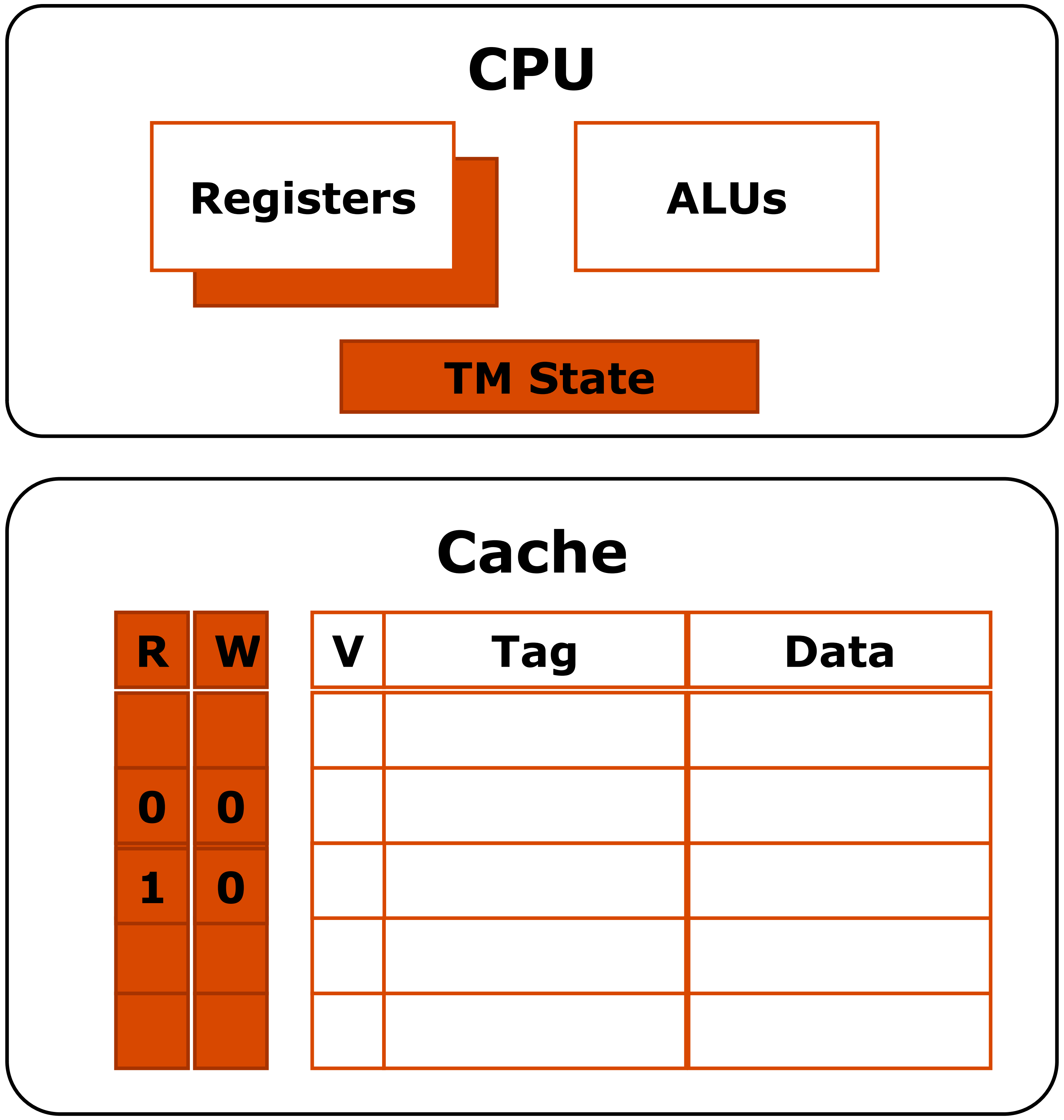


R	W	V	Tag	Data
0	0			

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

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

HTM transaction execution



CPU

Registers

ALUs

TM State

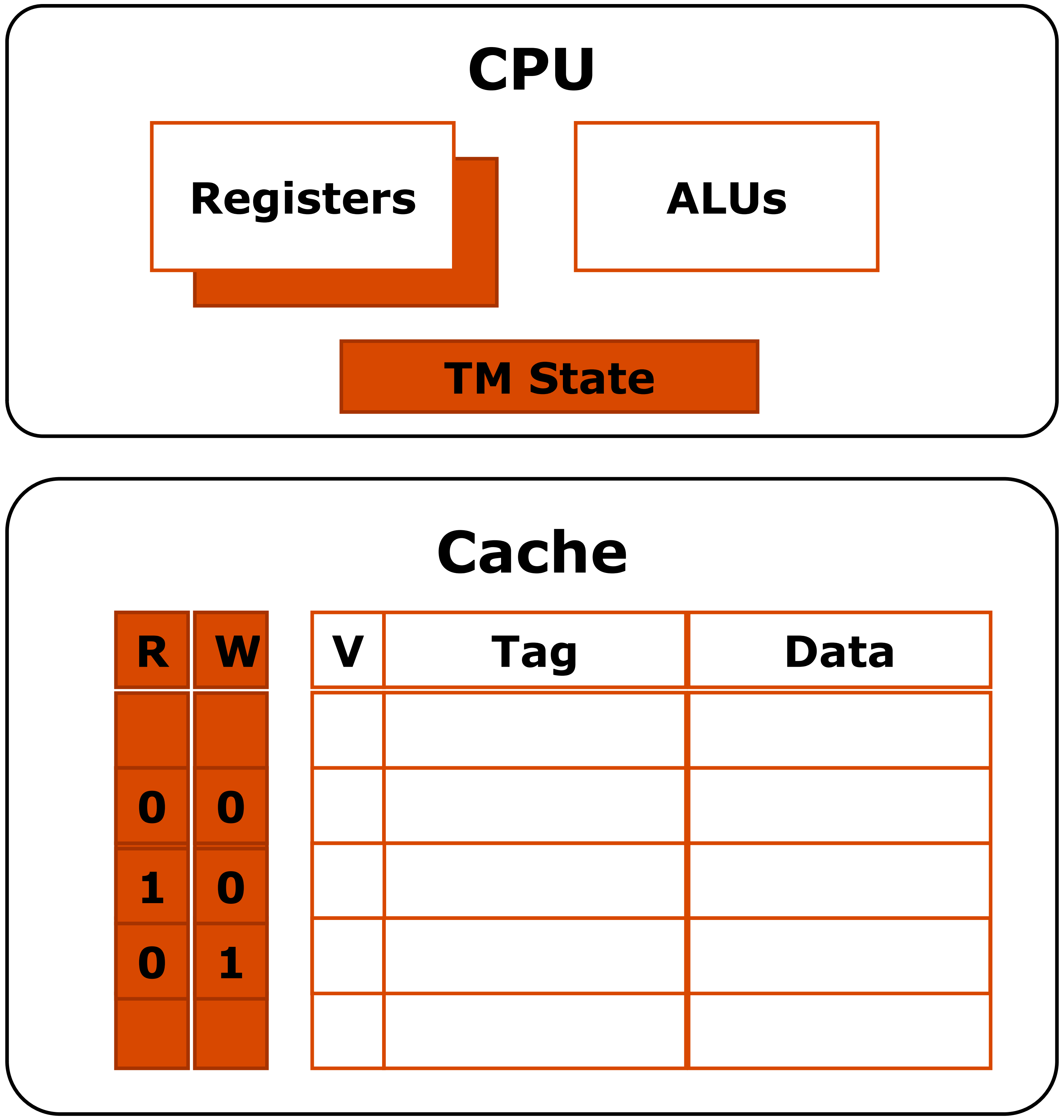
Cache

R	W	V	Tag	Data
0	0			
1	0			

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

- Load operation
  - Serve cache miss if needed
  - Mark data as part of read-set

HTM transaction execution

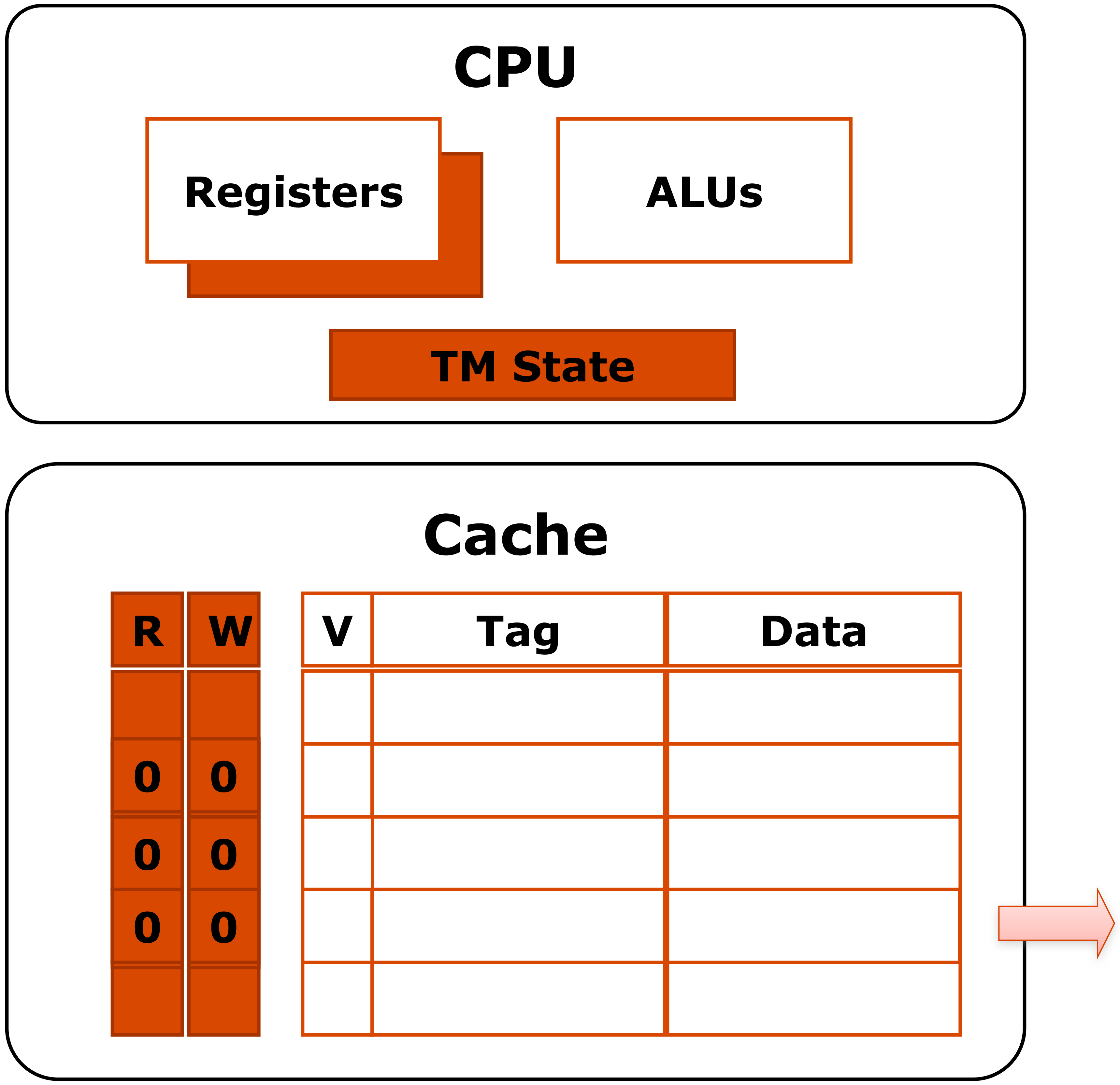


R	W	V	Tag	Data
0	0			
1	0			
0	1			

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

- Store operation
  - Serve cache miss if needed (**eXclusive** if not shared, **Shared** otherwise)
  - Mark data as part of write-set

HTM transaction execution

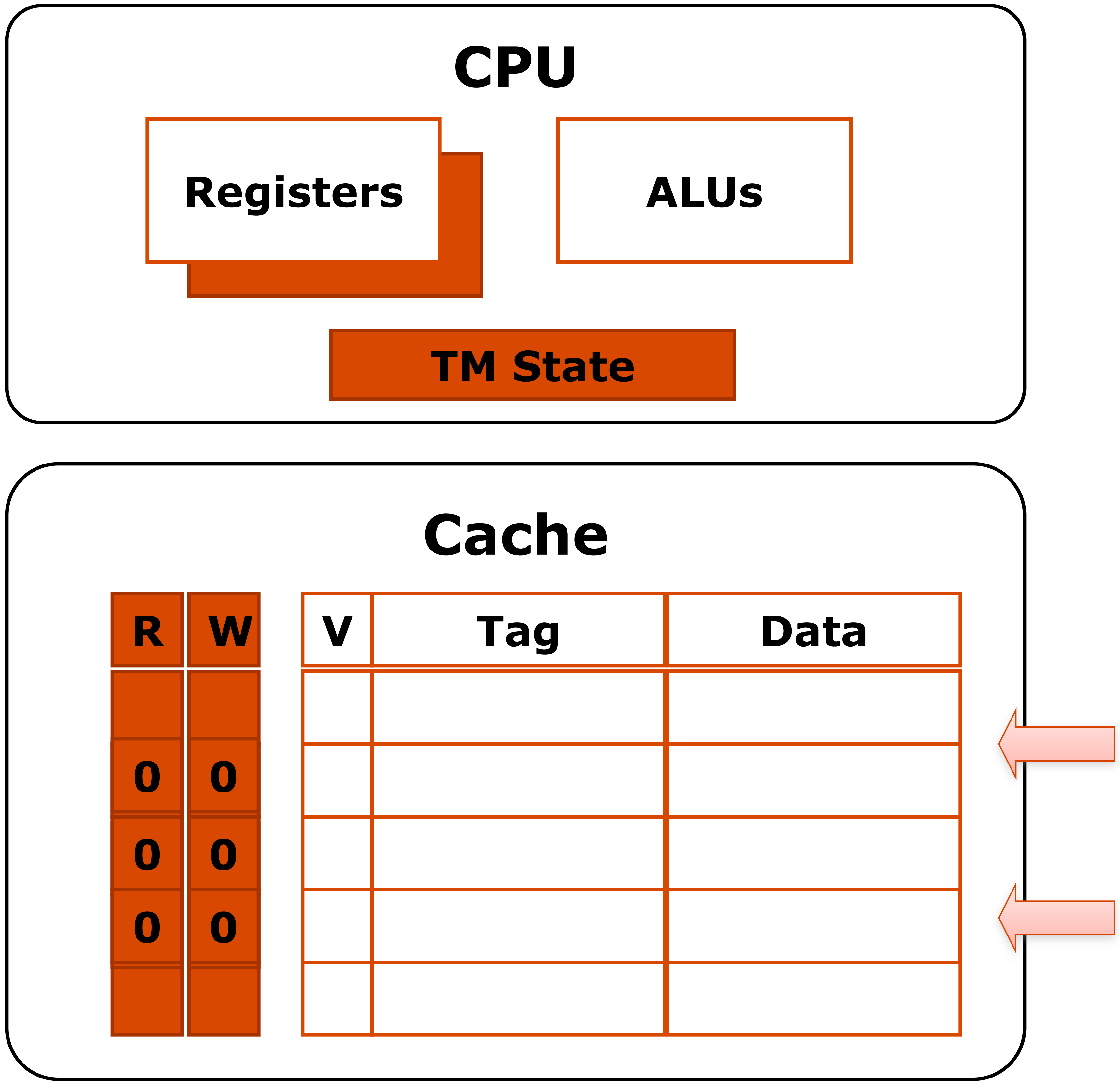


upgradeX B

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

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

HTM conflict detection



R	W	V	Tag	Data
0	0			
0	0			
0	0			

```
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

Transactional memory summary

- Atomic construct: declaration of atomic behavior
  - Motivating idea: increase simplicity of synchronization, without sacrificing performance
- Transactional memory implementation
  - Many variants have been proposes: SW, HW, SW+HW
  - Differ in versioning policy (eager vs. lazy)
  - Conflict detection policy (pessimistic vs. optimistic)
  - Detection granularity
- Hardware transactional memory
  - Versioned data kept in caches
  - Conflict detection built upon coherence protocol