Lecture 17:

Transactional Memory

Parallel Computing
Stanford CS149, Fall 2025

Raising level of abstraction for synchronization

Previous topic: machine-level atomic operations

- Test-and-set, fetch-and-op, compare-and-swap, load linked-store conditional

Then we used these atomic operations to construct higher level synchronization primitives in software:

- Locks, barriers
- Lock-free data structures
- We've seen how it can be challenging to produce correct programs using these primitives (easy to create bugs that violate atomicity, create deadlock, etc.)

Today: raising level of abstraction for synchronization even further

- Idea: transactional memory

What you should know

What a transaction is

The difference (in semantics) between an atomic code block and lock/unlock primitives

The basic design space of transactional memory implementations

- **Data versioning policy**
- **Conflict detection policy**
- **Granularity of detection**

The basics of a software implementation of transactional memory

The basics of a hardware implementation of transactional memory (consider how it relates to the cache coherence protocol implementations we've discussed previously in the course)

Between a Lock and a Hard Place

Locks force trade-off between

- Degree of concurrency ⇒ performance
- Chance of races, deadlock ⇒ correctness

Coarse grain locking

- low concurrency, higher chance of correctness
  - E.g. single lock for the whole data structure or all shared memory

Fine grain locking

- high concurrency, lower chance of correctness
  - E.g. hand-over-hand locking

Is there a better synchronization abstraction?

Review: ensuring atomicity via locks

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

Deposit is a read-modify-write operation: want "deposit" to be atomic with respect to other bank operations on this account

Locks are one mechanism to synchronize threads to ensure atomicity of update (via ensuring mutual exclusion on the account)

Programming with transactions

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

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

Atomic construct is declarative

- Programmer states what to do (maintain atomicity of this code), not how to do it
- No explicit use or management of locks

System implements synchronization as necessary to ensure atomicity

- System could implement atomic { } using locks (see this later)
- Implementation discussed today uses optimistic concurrency: maintain serialization only in situations of true contention (R-W or W-W conflicts)

Declarative vs. Imperative Abstractions

Declarative: programmer defines what should be done

- **Execute all these independent 1000 tasks**
- **Perform this set of operations atomically**

Imperative: programmer states how it should be done

- **Spawn N worker threads. Assign work to threads by removing work from a shared task queue**
- **Acquire a lock, perform operations, release the lock**

Transactional Memory (TM) Semantics

Memory transaction

- An atomic and isolated sequence of memory accesses
- Inspired by database transactions

Atomicity (all or nothing)

- Upon transaction commit, all memory writes in transaction take effect at once
- On transaction abort, none of the writes appear to take effect (as if transaction never happened)

Isolation

- No other processor can observe writes before transaction commits

Serializability

- Transactions appear to commit in a single serial order
- But the exact order of commits is not guaranteed by semantics of transaction

Transactional Memory (TM)

In other words… many of the properties we maintained for a single address in a coherent memory system, we'd like to maintain for sets of reads and writes in a transaction.

Transaction:
Reads: X, Y, Z
Writes: A, X

These memory transactions will either all be observed by other processors, or none of them will. (the effectively all happen at the same time)

What is the consistency model for TM?

Motivating transactional memory

Java HashMap

Map: Key ⟶ Value

- Implemented as a hash table with linked list per bucket

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

Bad: not thread safe (when synchronization needed)

Good: no lock overhead when synchronization not needed

Synchronized HashMap

Java 1.4 solution: synchronized layer

- Convert any map to thread-safe variant
- Uses explicit, coarse-grained mutual locking specified by programmer

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

Coarse-grain synchronized HashMap

- Good: thread-safe, easy to program
- Bad: limits concurrency, poor scalability

Review from earlier fine-grained sync lecture

What are solutions for making Java's HashMap thread-safe?

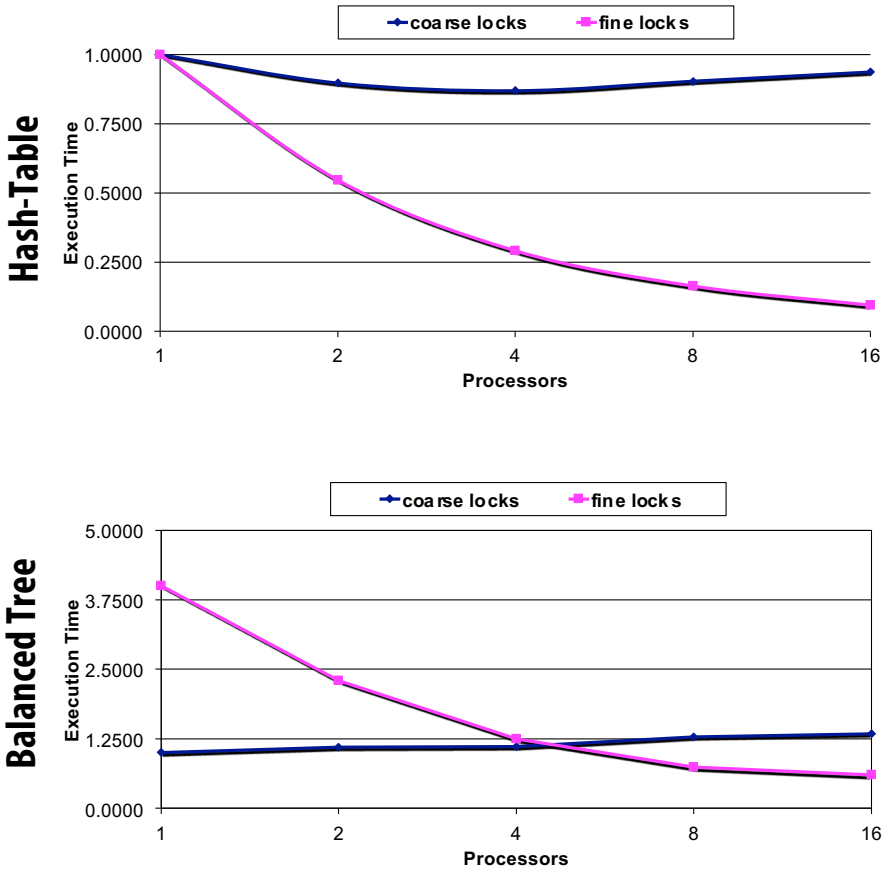
```
public Object get(Object key)  {
  int idx = hash(key);              // compute hash
  HashEntry e = buckets[idx];       // find bucket
  while (e != null)  {              // find element in bucket
    if (equals(key, e.key))
      return e.value;
    e = e.next;
  }
  return null;
}
```

One solution: use finer-grained synchronization (e.g., lock per bucket)

- Now thread safe: but incurs lock overhead even if synchronization not needed

Review: performance of fine-grained locking

Reducing contention via fine-grained locking leads to better performance



Transactional HashMap

Simply enclose all operation in atomic block

- Semantics of atomic block: system ensures atomicity of logic within block

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

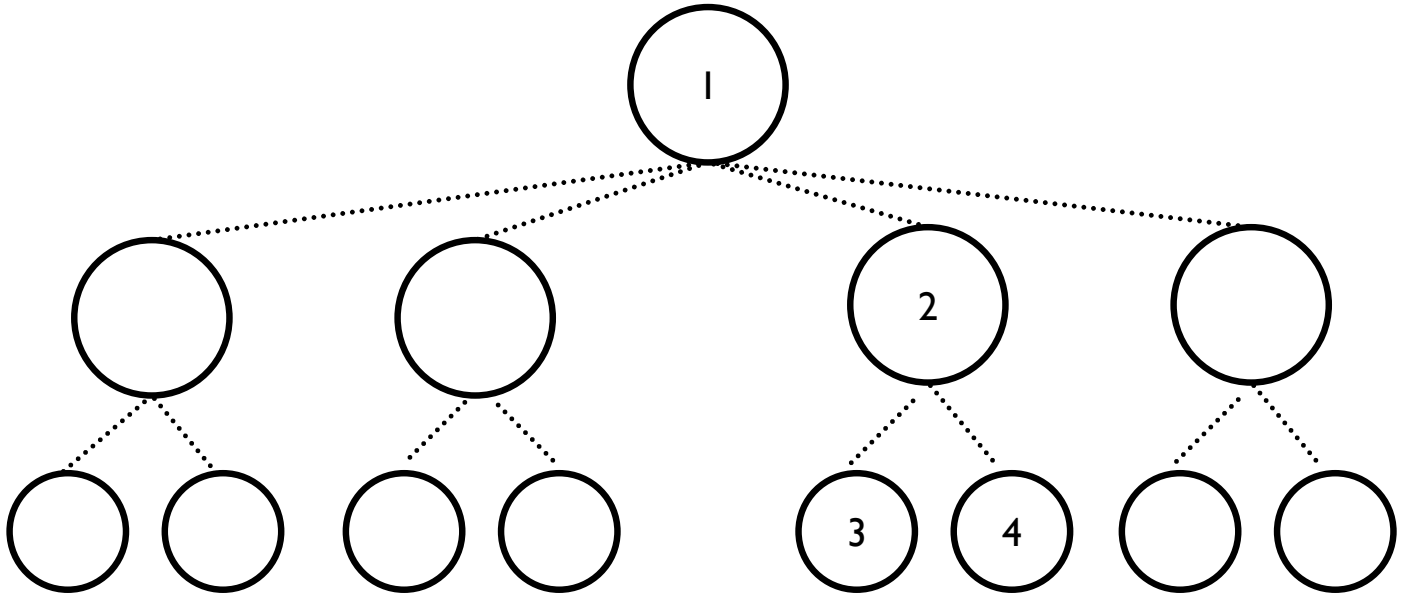
Good: thread-safe, easy to program

What about performance and scalability?

- Depends on the workload and implementation of atomic (to be discussed)

Another example: tree update by two threads

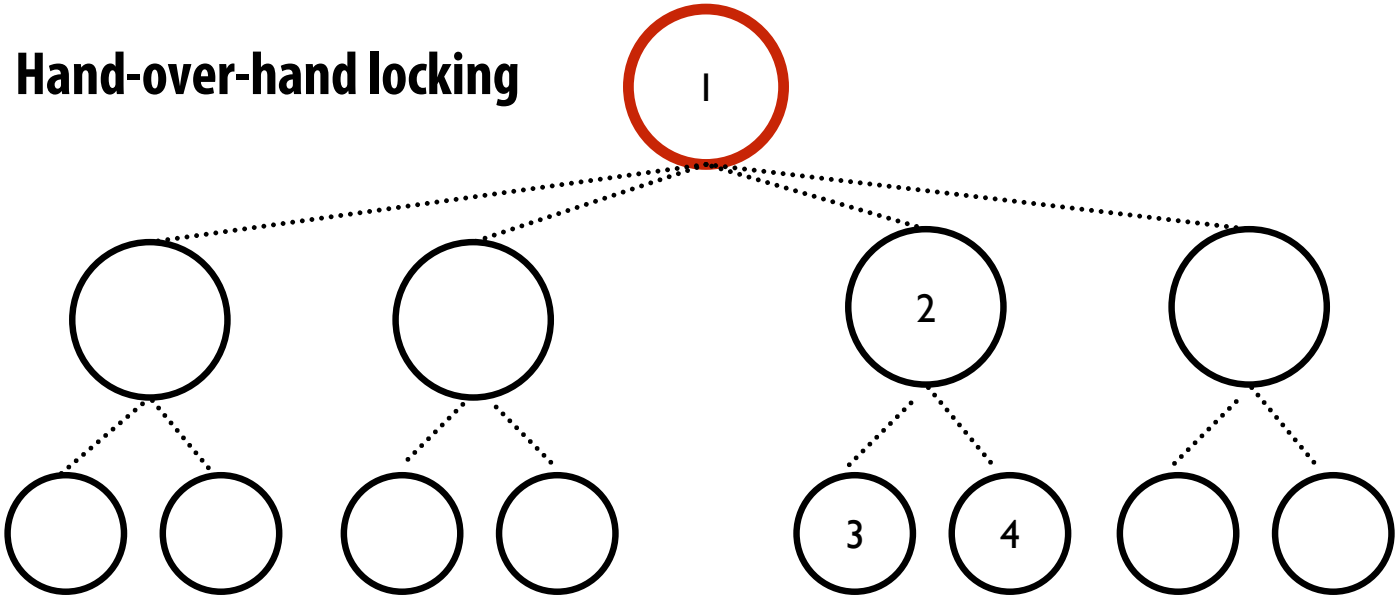
Goal: modify nodes 3 and 4 in a thread-safe way



Fine-grained locking example

Goal: modify nodes 3 and 4 in a thread-safe way

Hand-over-hand locking



Fine-grained locking example

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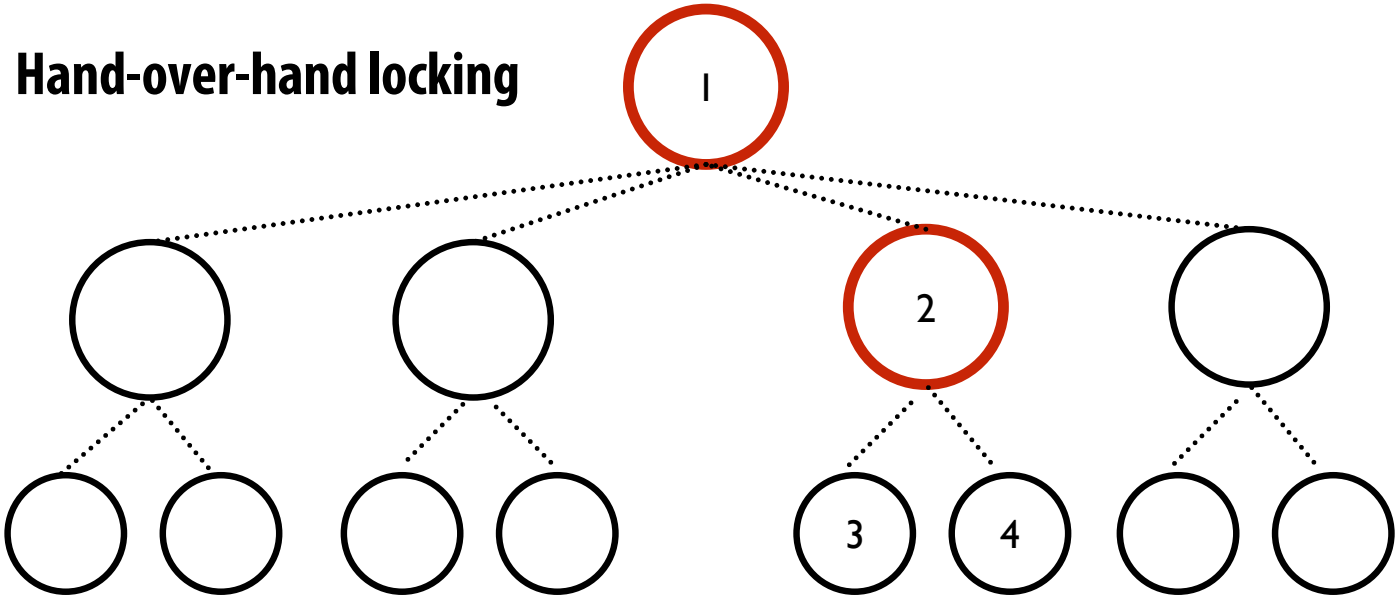
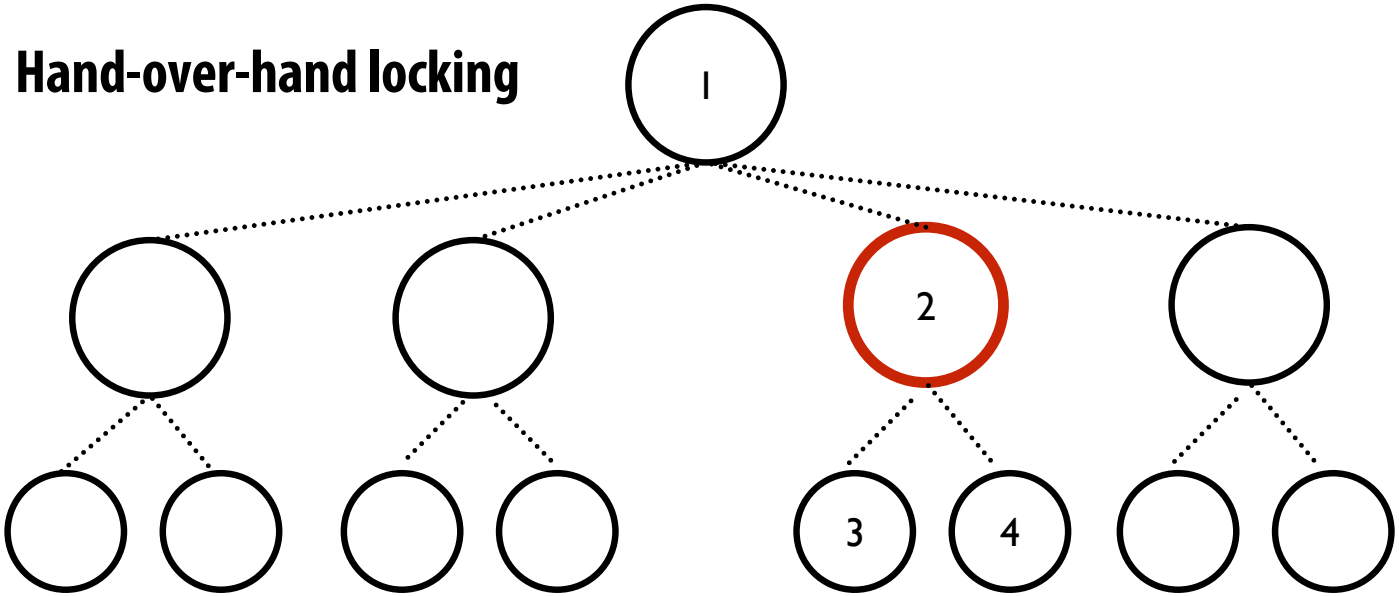


Fine-grained locking example

Goal: modify nodes 3 and 4 in a thread-safe way

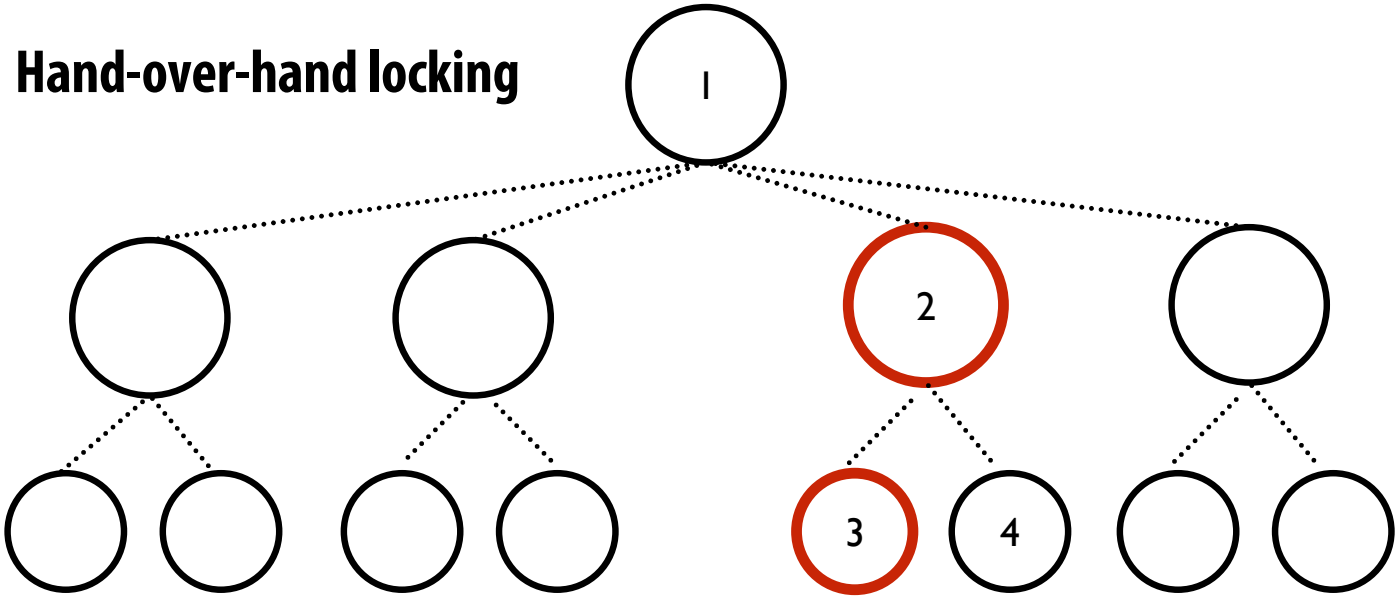
Hand-over-hand locking



Fine-grained locking example

Goal: modify nodes 3 and 4 in a thread-safe way

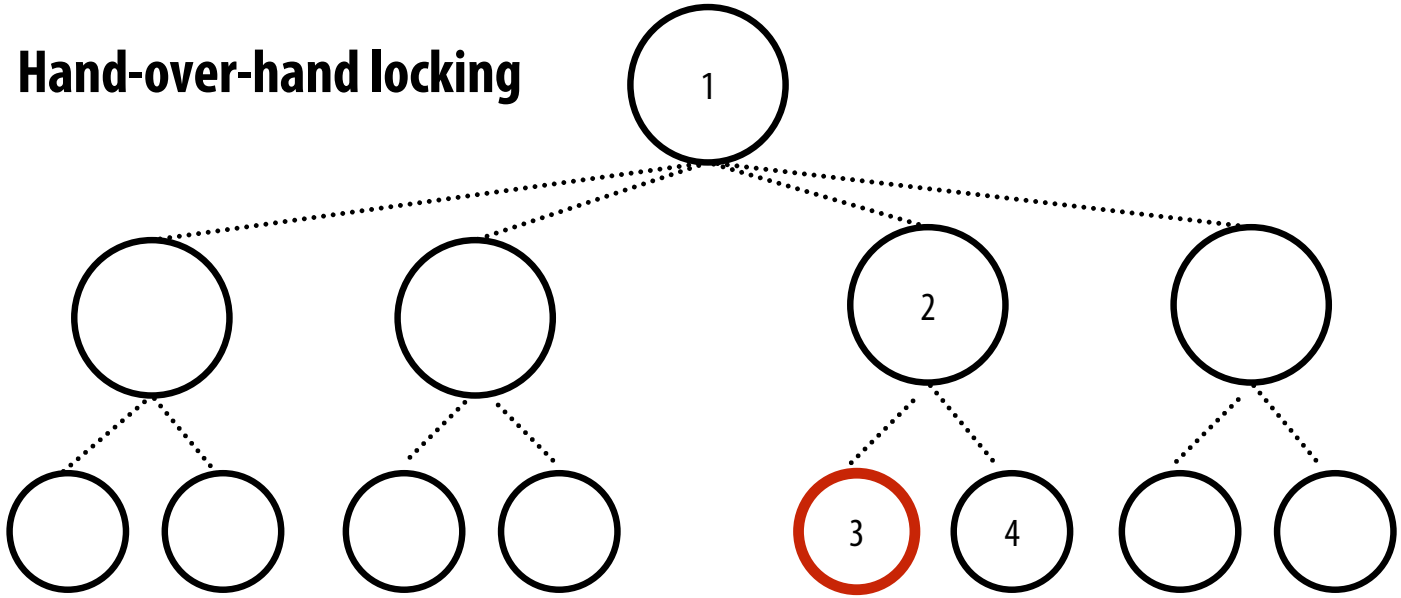
Hand-over-hand locking



Fine-grained locking example

Goal: modify nodes 3 and 4 in a thread-safe way

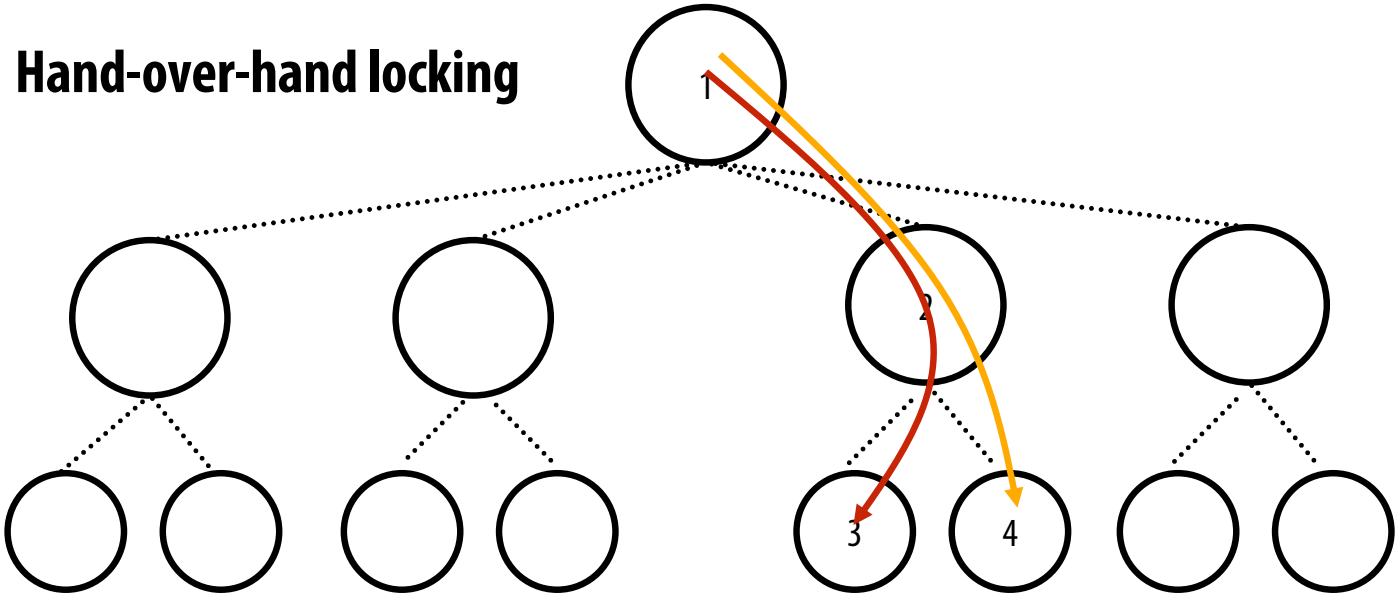
Hand-over-hand locking



Fine-grained locking example

Goal: modify nodes 3 and 4 in a thread-safe way

Hand-over-hand locking

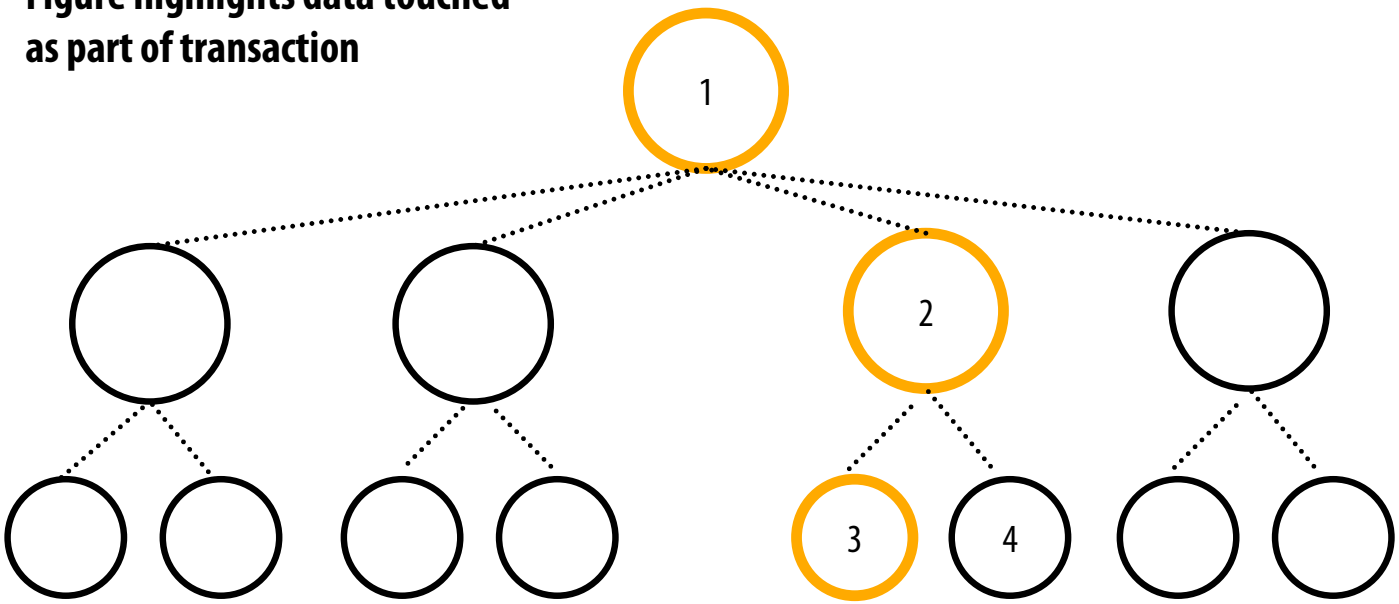


Locking can prevent concurrency

(here: locks on node 1 and 2 during update to node 3 could delay update to 4)

Transactions example

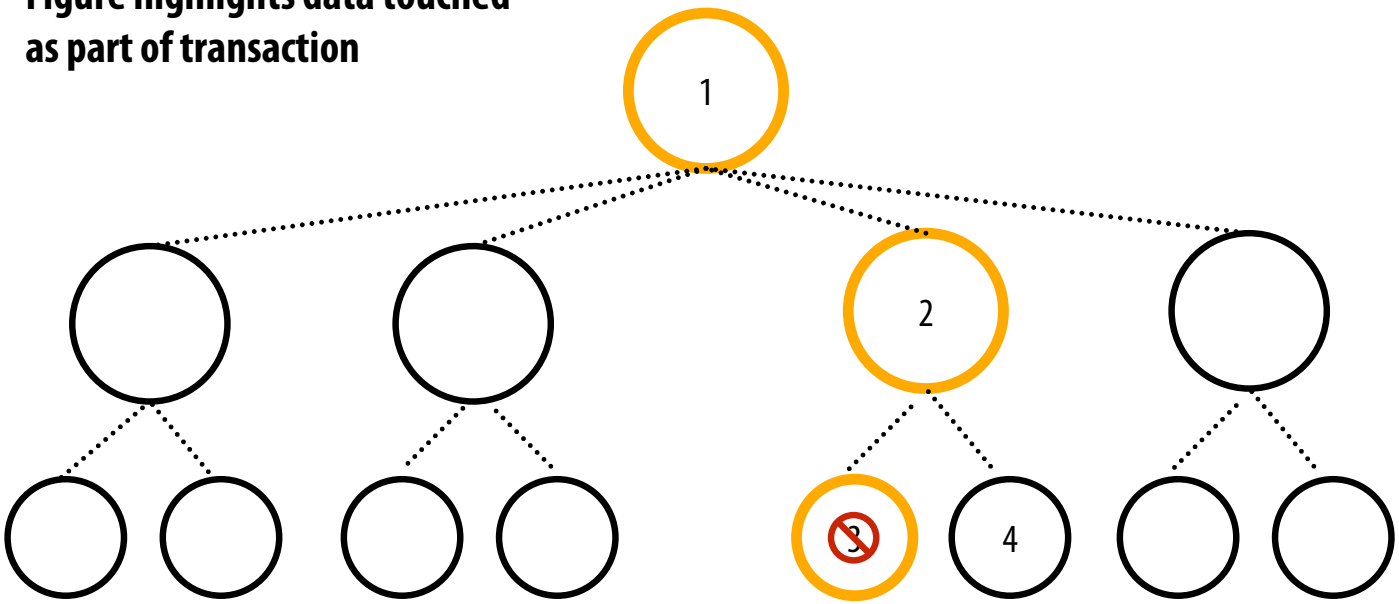
Figure highlights data touched as part of transaction



Transaction A
READ: 1, 2, 3

Transactions example

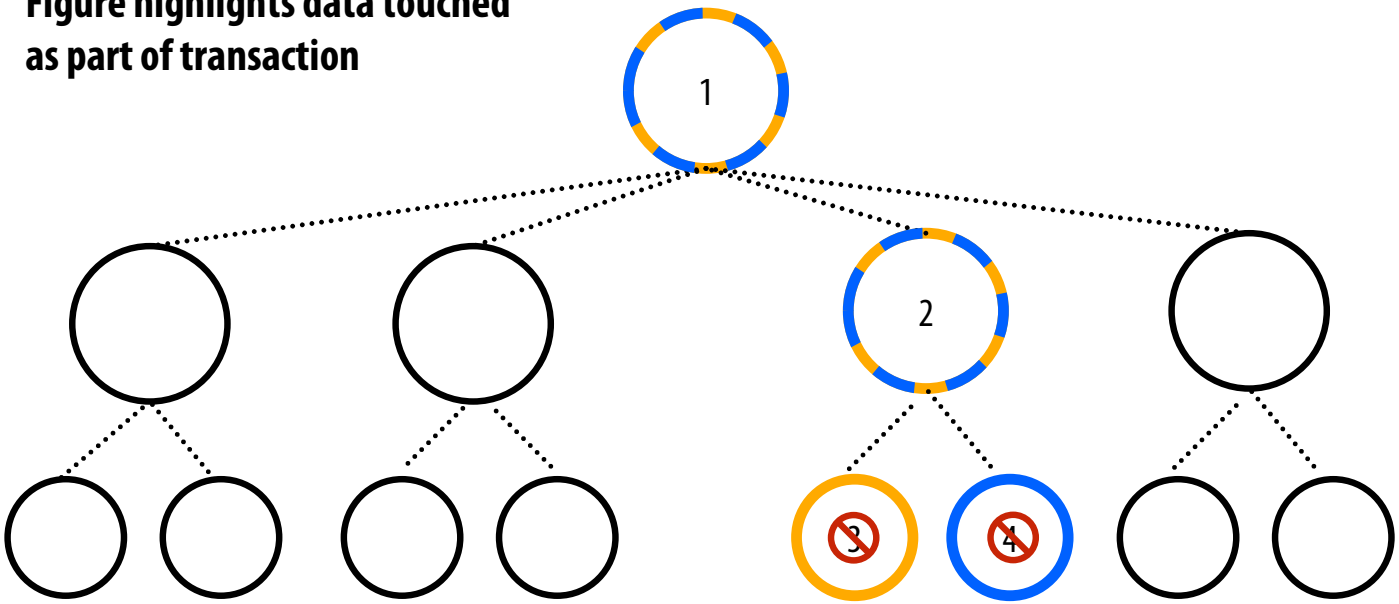
Figure highlights data touched as part of transaction



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

Transactions example

Figure highlights data touched as part of transaction



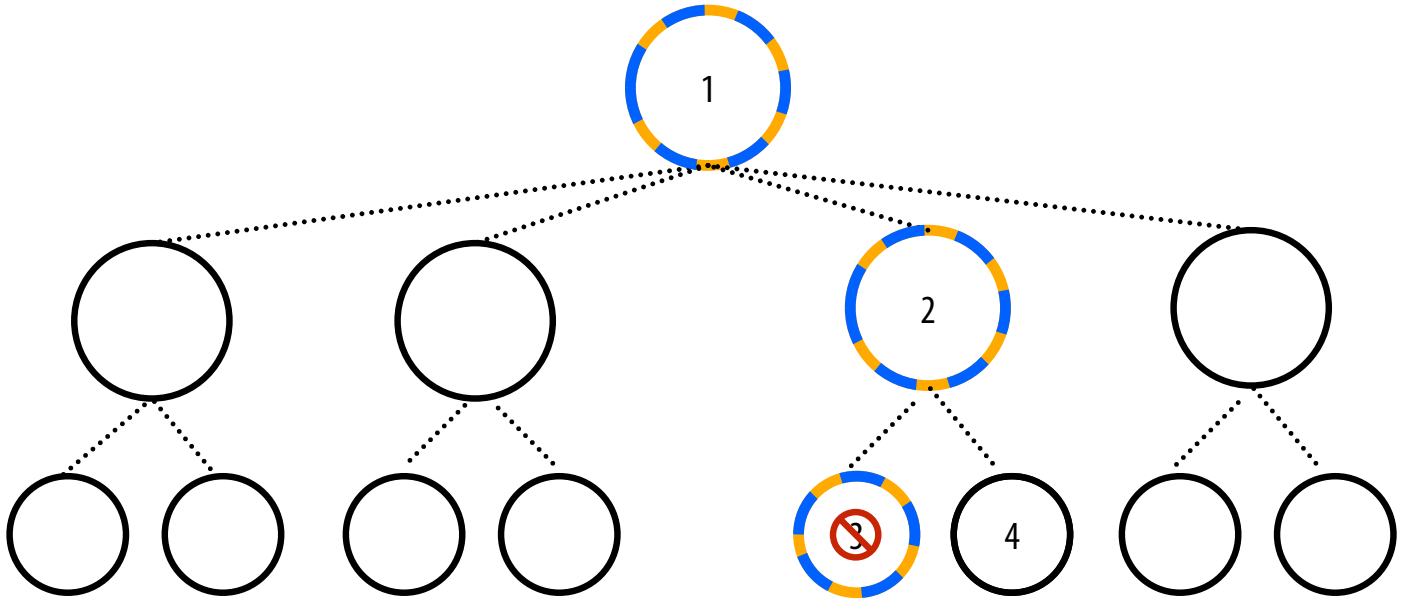
Transaction A
READ: 1, 2, 3
WRITE: 3

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

NO READ-WRITE or WRITE-WRITE conflicts!
(no transaction writes to data that is accessed by other transactions)

Transactions example #2

(Both transactions modify node 3)



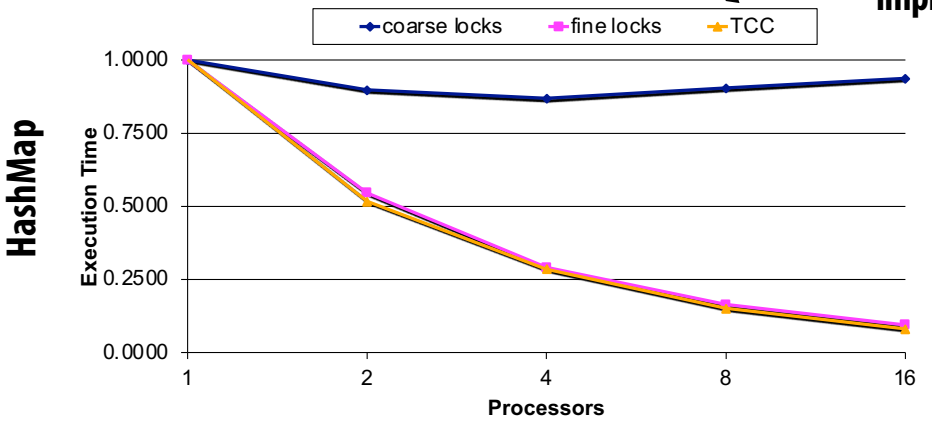
Transaction A
READ: 1, 2, 3
WRITE: 3

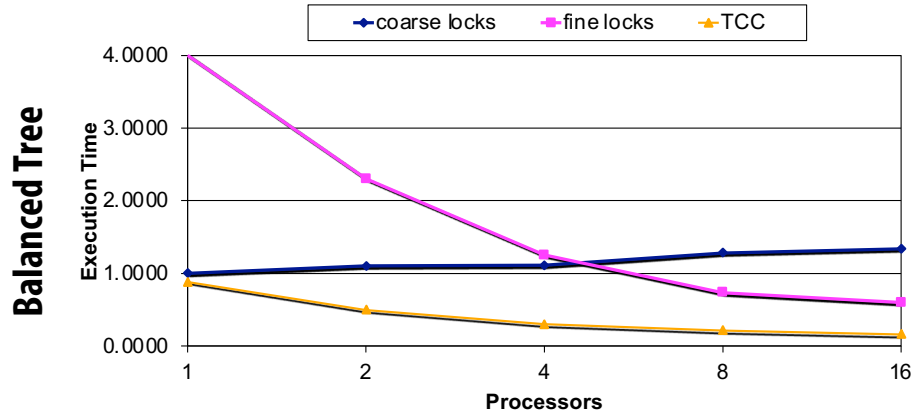
Transaction B
READ: 1, 2, 3
WRITE: 3

Conflicts exist: transactions must be serialized
(both transactions write to node 3)

Performance: locks vs. transactions

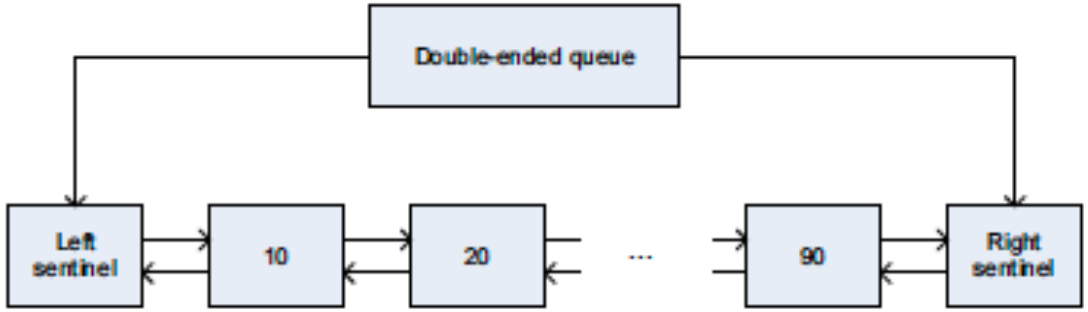
"TCC" is a TM system implemented in hardware





Atomic and Doubly-Linked List

Make PushLeft method on a doubly-linked list thread safe using atomic()




```
void PushLeft(DQueue *q, int val) {
    QNode *qn = malloc(sizeof(QNode));
    qn->val = val;
    QNode *leftSentinel = q->left;
    QNode *oldLeftNode = leftSentinel->right;
    qn->left = leftSentinel;
    qn->right = oldLeftNode;
    leftSentinel->right = qn;
    oldLeftNode->left = qn;
}
```

Another motivation: failure atomicity

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

Complexity of manually catching exceptions

- Programmer provides "undo" code on a case-by-case basis
- Complexity: must track 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 now responsible for processing exceptions

- All exceptions (except those explicitly managed by the programmer)
- Transaction is aborted and memory updates are undone
- Recall: a transaction either commits or it doesn't: no partial updates are visible to other threads
  - E.g., no locks held by a failing threads…

Another motivation: composability

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

Thread 0:
`transfer(A, B, 100)`

Thread 1:
`transfer(B, A, 200)`

DEADLOCK!

Composing lock-based code can be tricky

- Requires system-wide policies to get correct
- System-wide policies can break software modularity

Programmer caught between a lock and a hard place !

- Coarse-grain locks: low performance
- Fine-grain locking: good for performance, but mistakes can lead to deadlock

Composability: locks

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

DEADLOCK!

```
void transfer(B, A, amount) {
  synchronized(B) {
    synchronized(A) {
      withdraw(A, 2*amount);
      deposit(B, 2*amount);
    }
  }
}
```

Composing lock-based code can be tricky

- Requires system-wide policies to get correct
- System-wide policies can break software modularity

Programmer caught between and lock and a hard place

- Coarse-grain locks: low performance
- Fine-grain locking: good for performance, but mistakes can lead to deadlock

Composability: transactions

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

Thread 0:
`transfer(A, B, 100)`

Thread 1:
`transfer(B, A, 200)`

Transactions compose gracefully (in theory)

- Programmer declares global intent (atomic execution of transfer)
  - No need to know about global implementation strategy
- Transaction in `transfer` subsumes any defined in `withdraw` and `deposit`
  - Outermost transaction defines atomicity boundary

System manages concurrency as well as possible

- Serialization for transfer(A, B, 100) and transfer(B, A, 200)
- Concurrency for transfer(A, B, 100) and transfer(C, D, 200)

Advantages (promise) of transactional memory

Easy to use synchronization construct

- It is difficult for programmers to get synchronization right
- Programmer declares need for atomicity, system implements it well
- Claim: transactions are as easy to use as coarse-grain locks

Often performs as well as fine-grained locks

- Provides automatic read-read concurrency and fine-grained concurrency
- Performance portability: locking scheme for four CPUs may not be the best scheme for 64 CPUs
- Productivity argument for transactional memory: system support for transactions can achieve most of the benefit of expert programming with fined-grained locks, with much less development time

Failure atomicity and recovery

- No lost locks when a thread fails
- Failure recovery = transaction abort + restart

Composability

- Safe and scalable composition of software modules

Self-check: atomic { } ≠ lock() + unlock()

The difference

- Atomic: high-level declaration of atomicity
  - Does not specify implementation of atomicity

- Lock: low-level blocking primitive
  - Does not provide atomicity or isolation on its own

Make sure you understand this difference in semantics!

Keep in mind

- Locks can be used to implement an `atomic` block but…
- Locks can be used for purposes beyond atomicity
  - Cannot replace all uses of locks with atomic regions
- `Atomic` eliminates many data races, but programming with atomic blocks can still suffer from atomicity violations: e.g., programmer erroneous splits sequence that <u>should be</u> atomic into two atomic blocks

What about replacing synchronized with atomic in this example?

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

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

Atomicity violation due to programmer error

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

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

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

Programmer mistake: logically atomic code sequence (in thread 1) is erroneously separated into two atomic blocks (allowing another thread to set pointer to NULL in between)

Implementing transactional memory

Recall transactional semantics

Atomicity (all or nothing)

- At commit, all memory writes take effect at once
- In event of 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

- While maintaining as much concurrency as possible

Two key implementation questions

- Data versioning policy: How does the system manage uncommitted (new) and previously committed (old) versions of data for concurrent transactions?

- Conflict detection policy: how/when does the system determine that two concurrent transactions conflict?

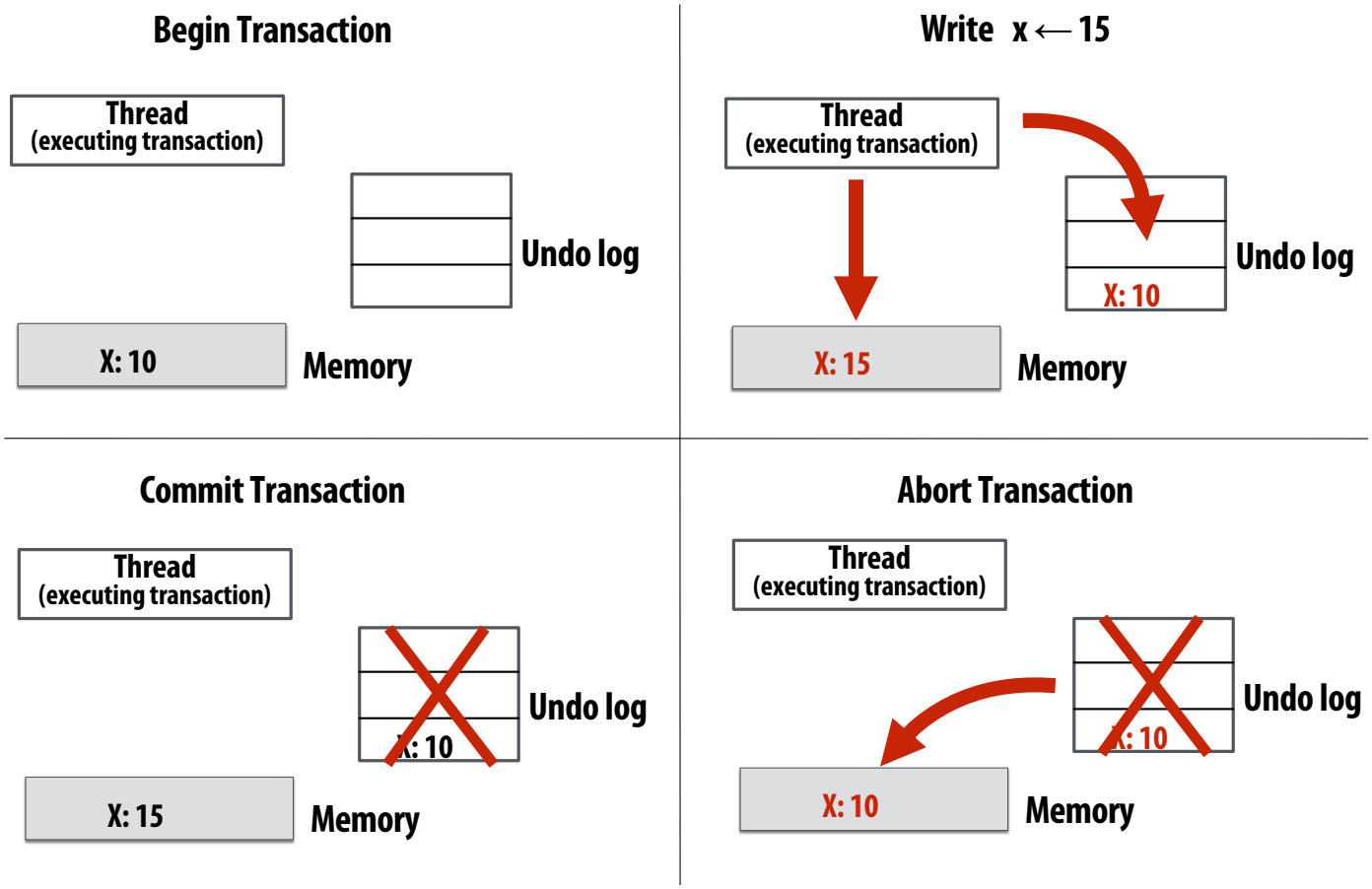
Data versioning policy

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

1. **Eager versioning (undo-log based)**
2. **Lazy versioning (write-buffer based)**

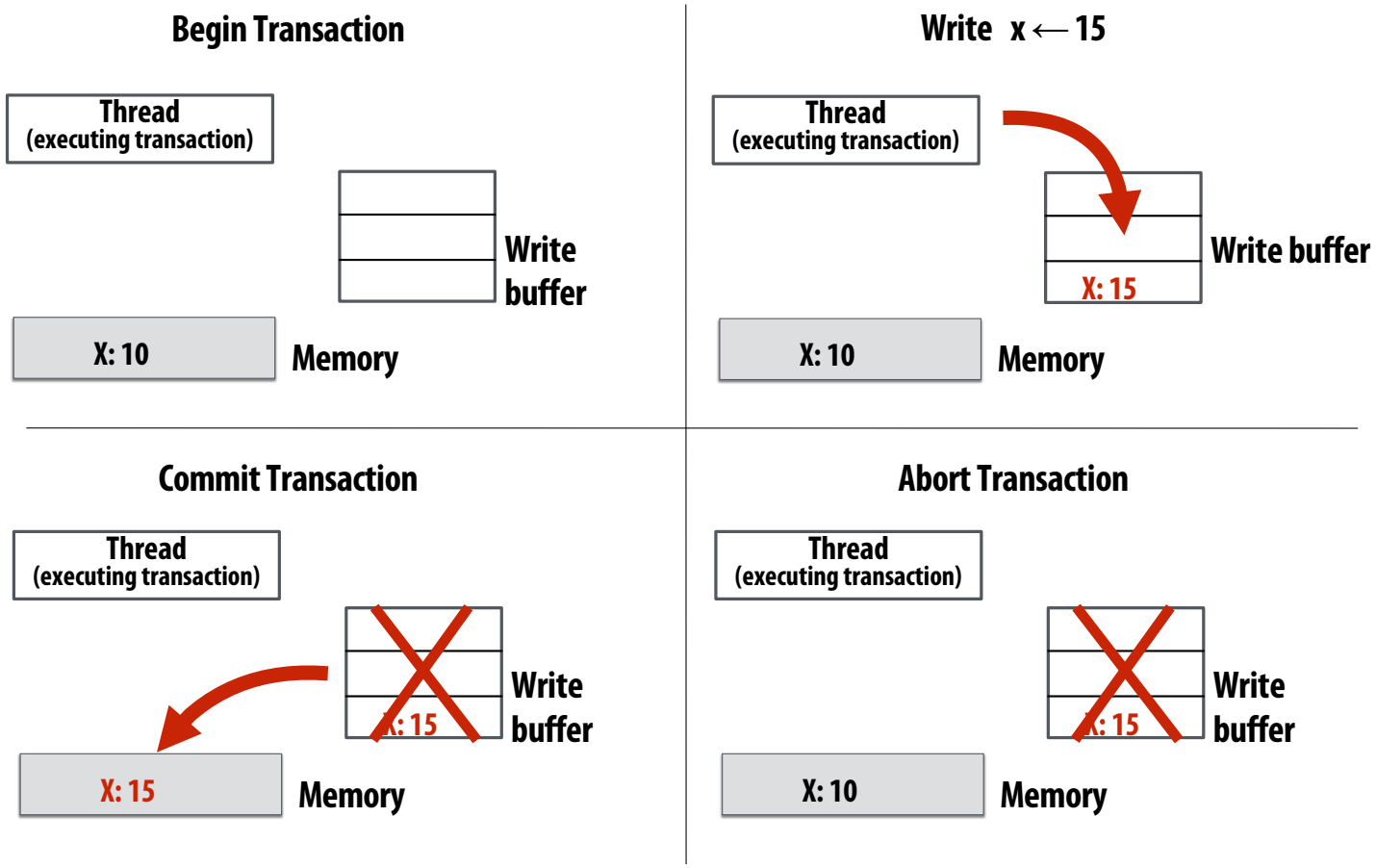
Eager versioning

Update memory immediately, maintain "undo log" in case of abort



Lazy versioning

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



Data versioning

Goal: manage uncommitted (new) and committed (old) versions of data for concurrent transactions

Eager versioning (undo-log based)

Eager versioning philosophy: write to memory immediately, hoping transaction won't abort (but deal with aborts when you have to)

- Update memory location directly on write
- Maintain undo information in a log (incurs per-store overhead)
- Good: faster commit (data is already in memory)
- Bad: slower aborts, fault tolerance issues (consider crash in middle of transaction)

Lazy versioning (write-buffer based)

Lazy versioning philosophy: only write to memory when you have to

- Buffer data in a write buffer until commit
- Update actual memory location on commit
- Good: faster abort (just clear log), no fault tolerance issues
- Bad: slower commits

Conflict detection

Must detect and handle conflicts between transactions

- Read-write conflict: transaction A reads address X, which was written to by pending (but not yet committed) transaction B
- Write-write conflict: transactions A and B are both pending, and both write to address X

System must track a transaction's read set and write set

- Read-set: addresses read during the transaction
- Write-set: addresses written during the transaction

Pessimistic detection

Check for conflicts (immediately) during loads or stores

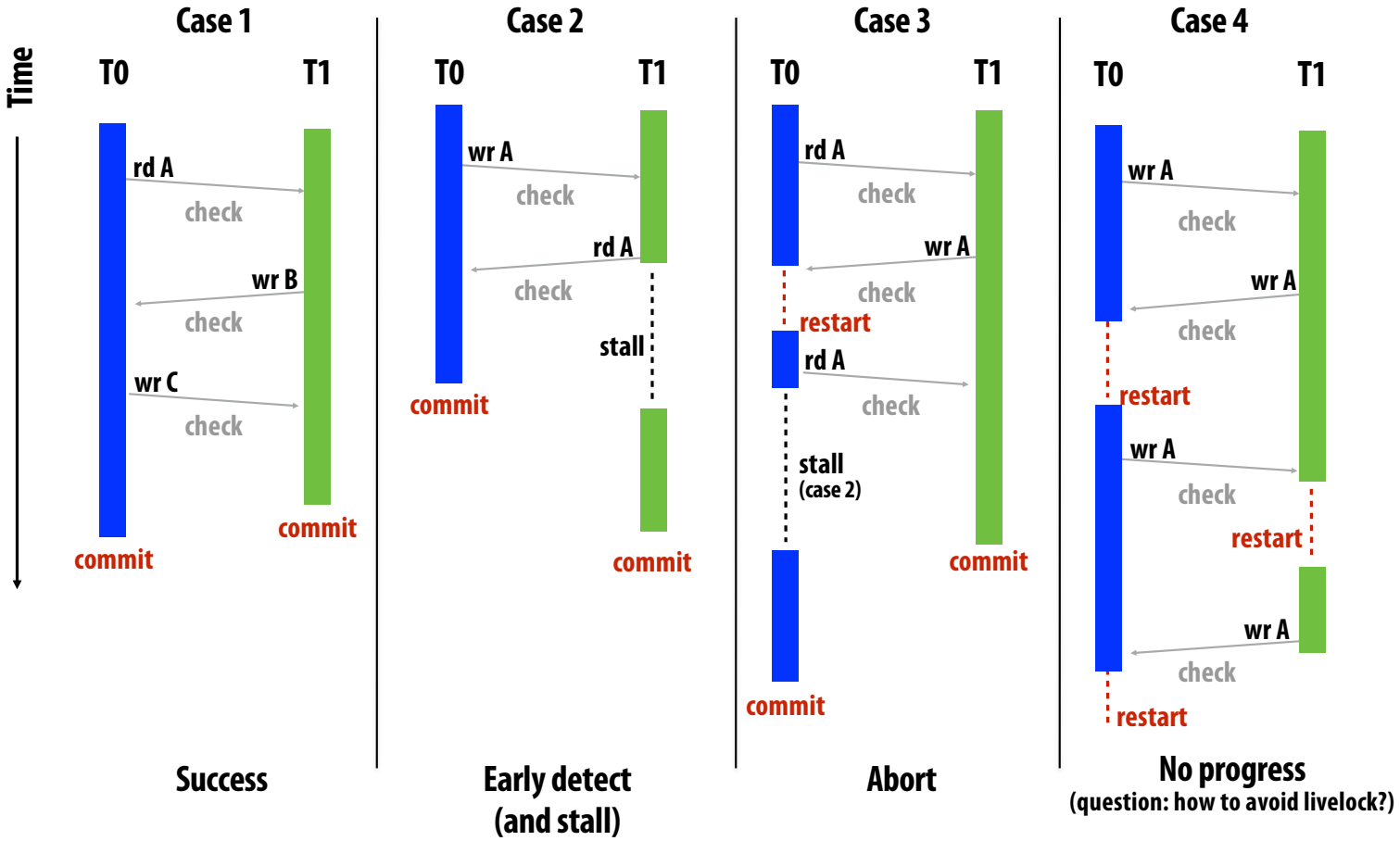
- Philosophy: "I suspect conflicts might happen, so let's always check to see if one has occurred after each memory operation… if I'm going to have to roll back, might as well do it now to avoid wasted work."

"Contention manager" decides to stall or abort transaction when a conflict is detected

- Various policies to handle common case fast

Pessimistic detection examples

Note: diagrams assume "aggressive" contention manager on writes: writer wins, so other transactions abort)



Optimistic detection

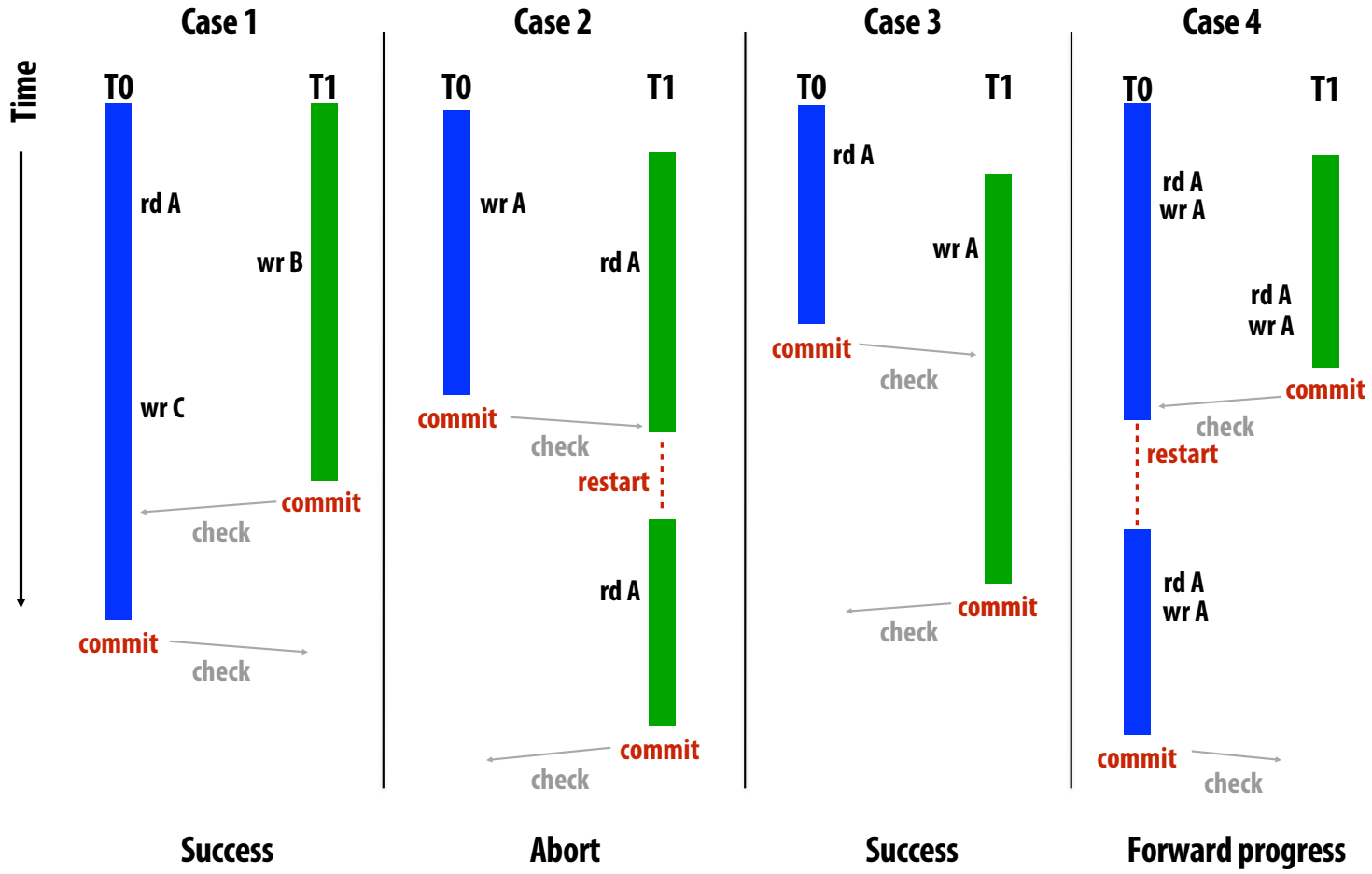
Detect conflicts when a transaction attempts to commit

- Intuition: "Let's hope for the best and sort out all the conflicts only when the transaction tries to commit"

On a conflict, give priority to committing transaction

- Other transactions may abort later on

Optimistic detection



Conflict detection trade-offs

Pessimistic conflict detection (a.k.a. "eager")

- Good: detect conflicts early (undo less work, turn some aborts to stalls)
- Bad: no forward progress guarantees, more aborts in some cases
- Bad: fine-grained communication (check on each load/store)

- Bad: detection on critical path

Optimistic conflict detection (a.k.a."lazy" or "commit")

- Good: forward progress guarantees
- Good: bulk communication and conflict detection
- Bad: detects conflicts late, can still have fairness problems