

# Transactional Memory

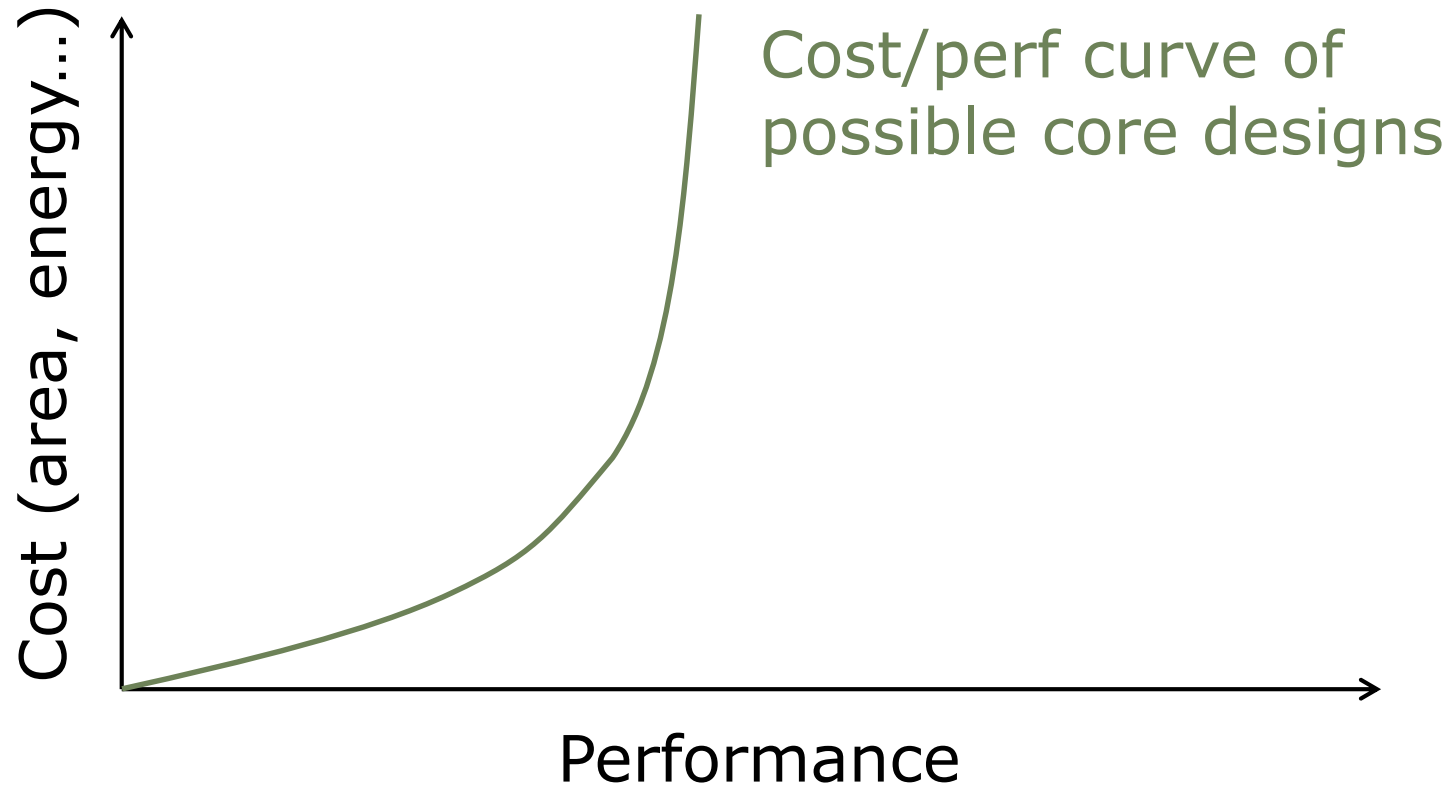
*Daniel Sanchez*

Computer Science & Artificial Intelligence Lab  
M.I.T.

*Based on slides from Christos Kozyrakis*

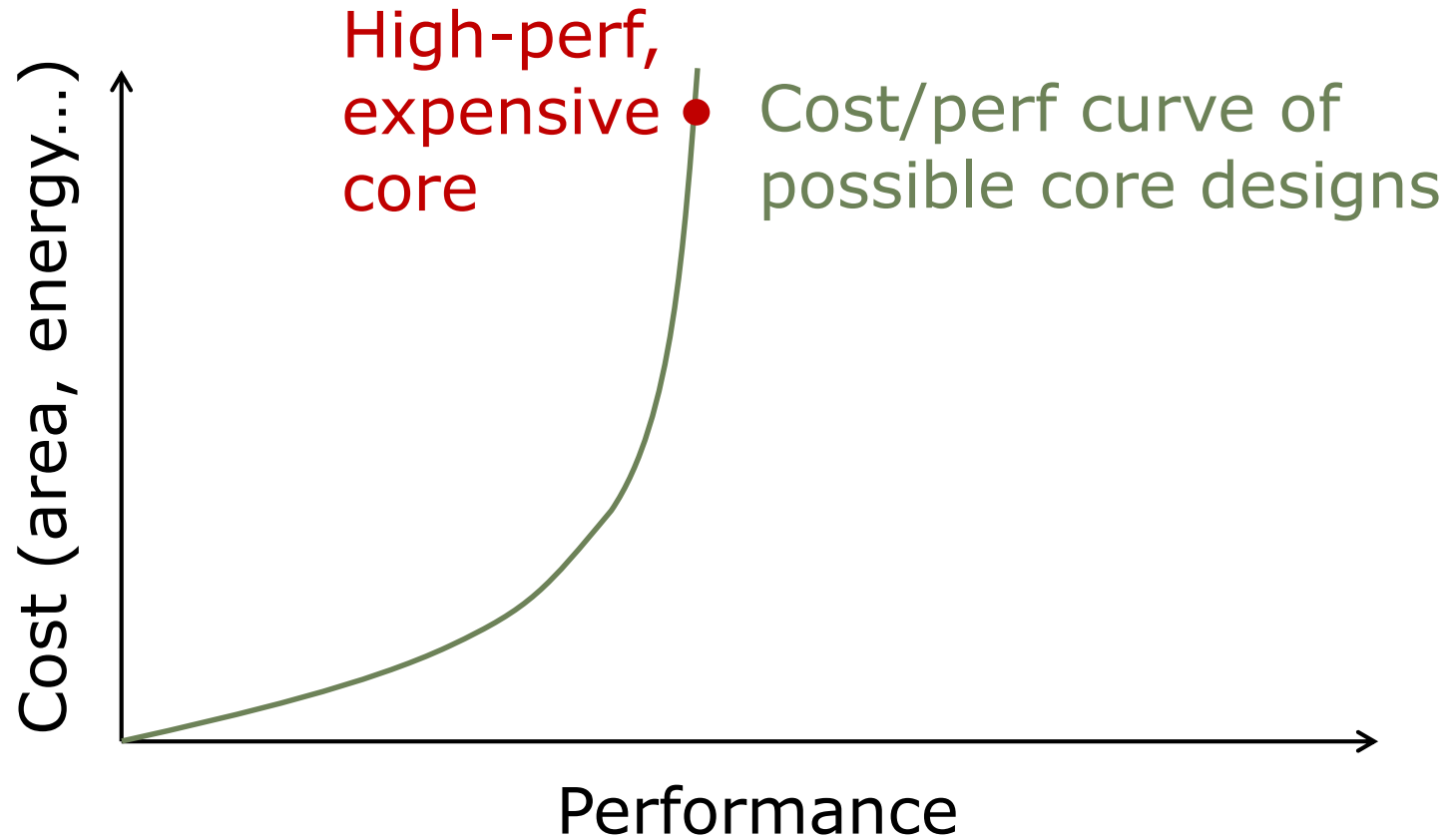
# Reminder: Why Multicore?

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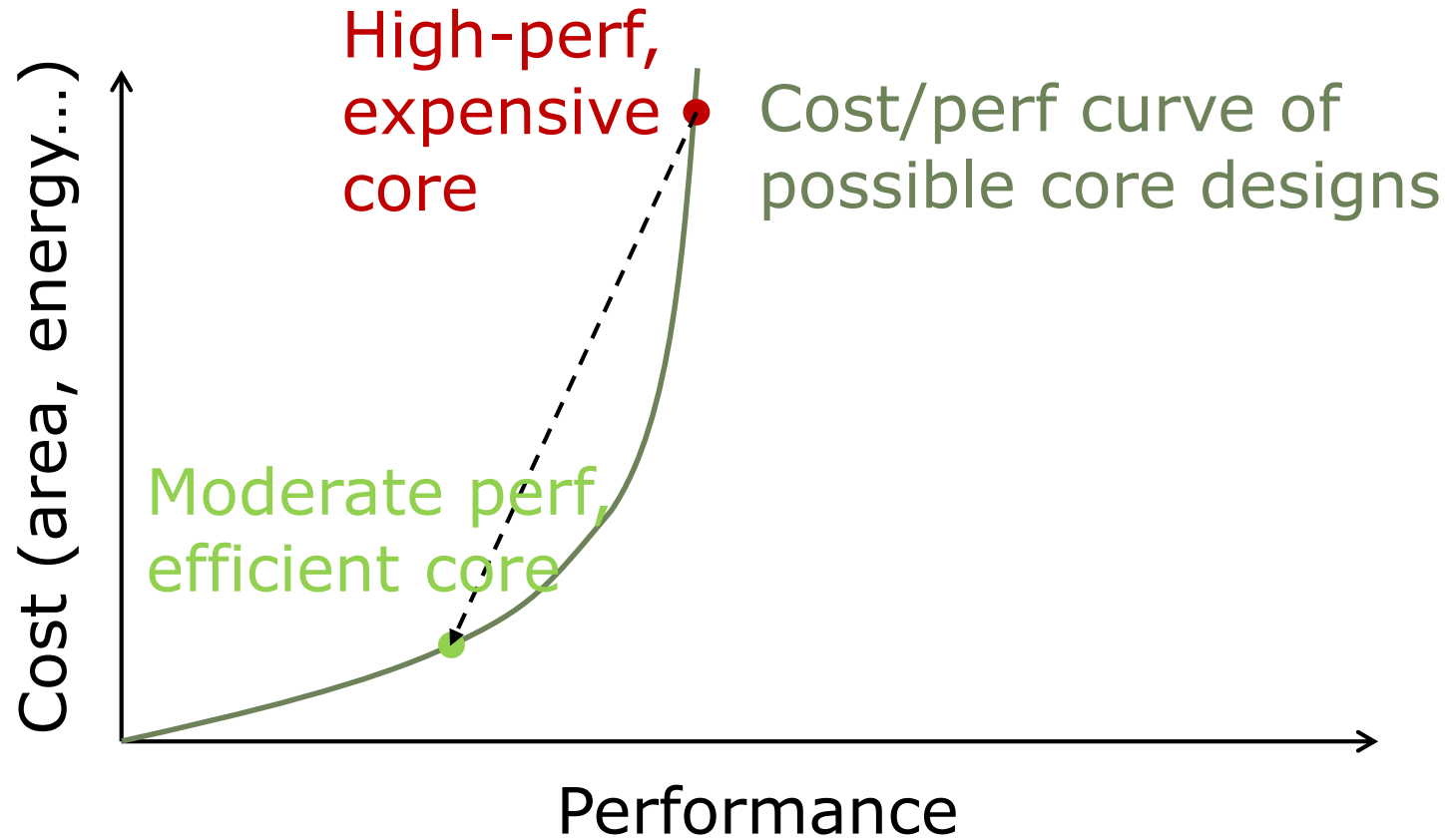
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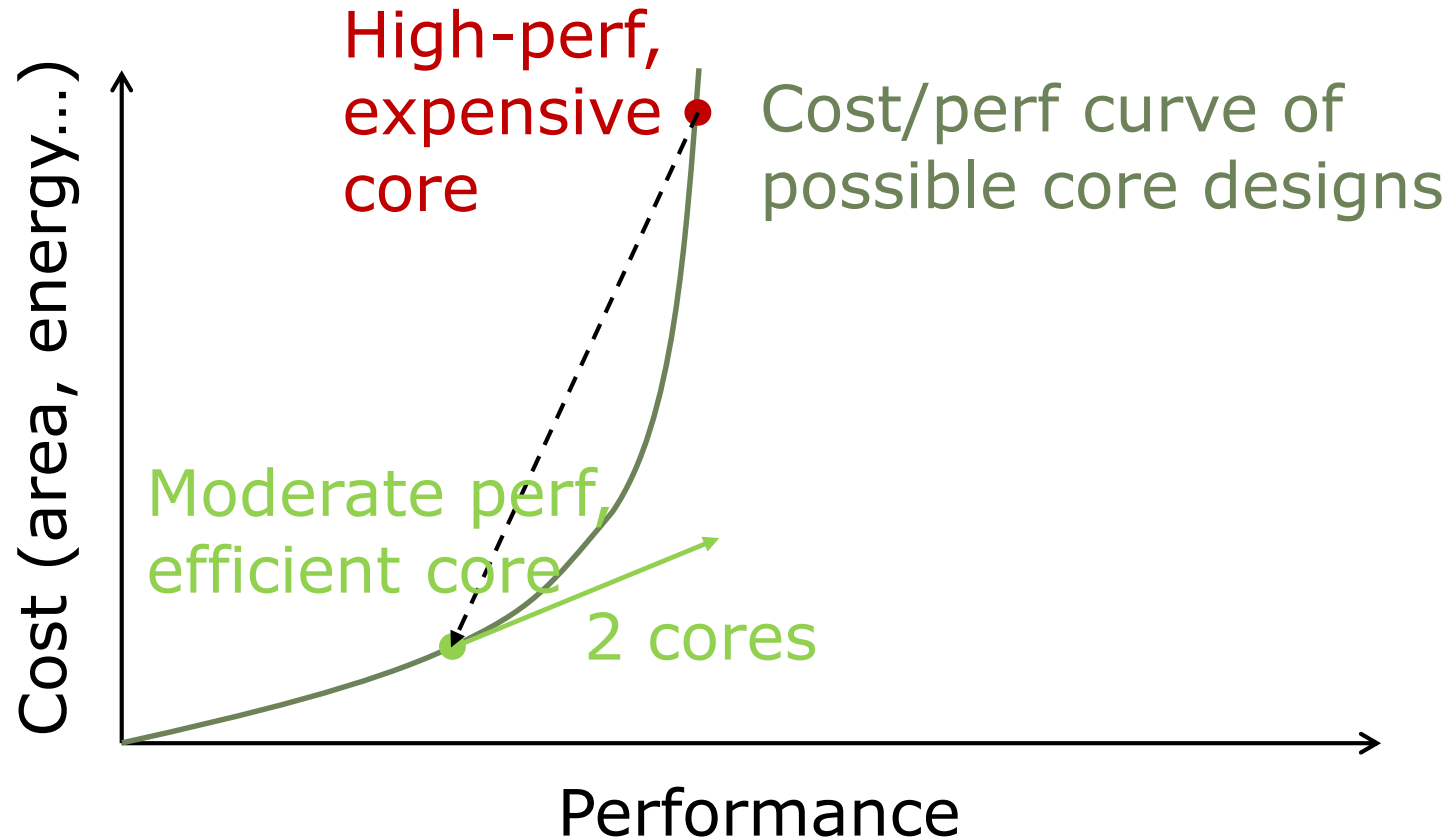
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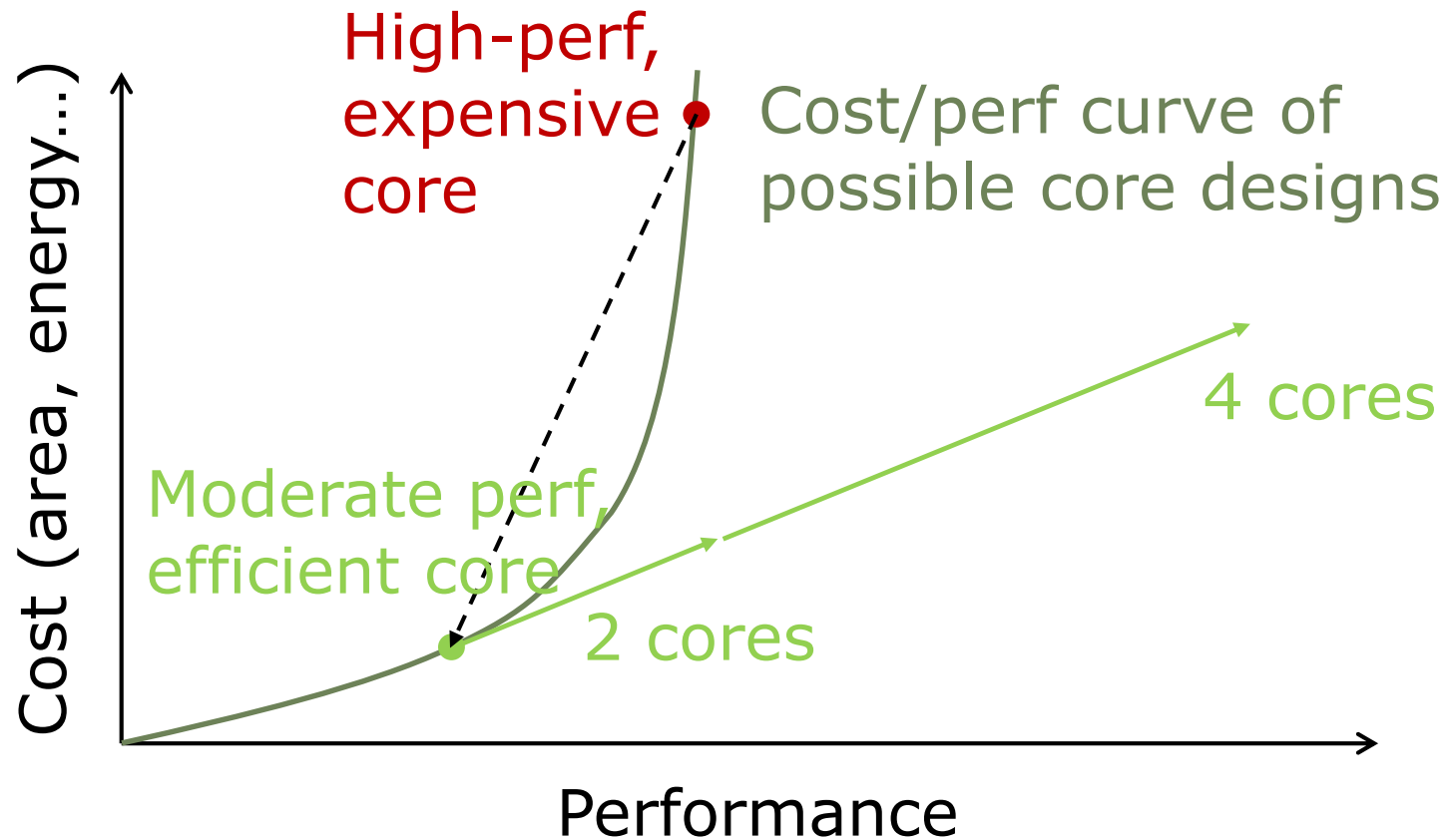
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# But Parallel Programming is HARD

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

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  - 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 (;;) {  
        if (buckets[idx].empty)  
            return NOT_FOUND;  
        if (buckets[idx].key == key)  
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```

- 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 (;;) {
        if (buckets[idx].empty) break;
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    unlock(mutex);
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- Also add lock(mutex)/unlock(mutex) pairs to all other hash table methods (insert, remove, ...)

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- 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

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- Per-bucket locks

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Locking overheads



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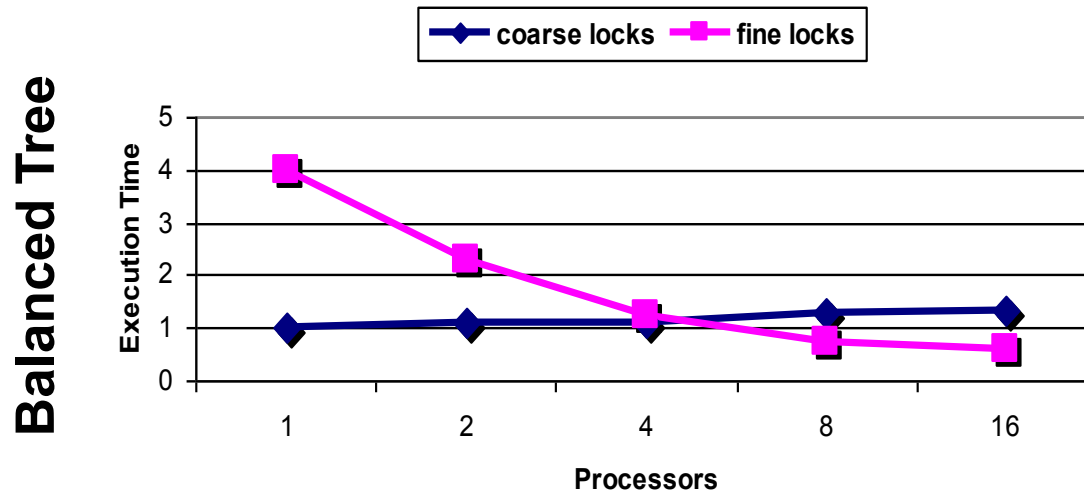
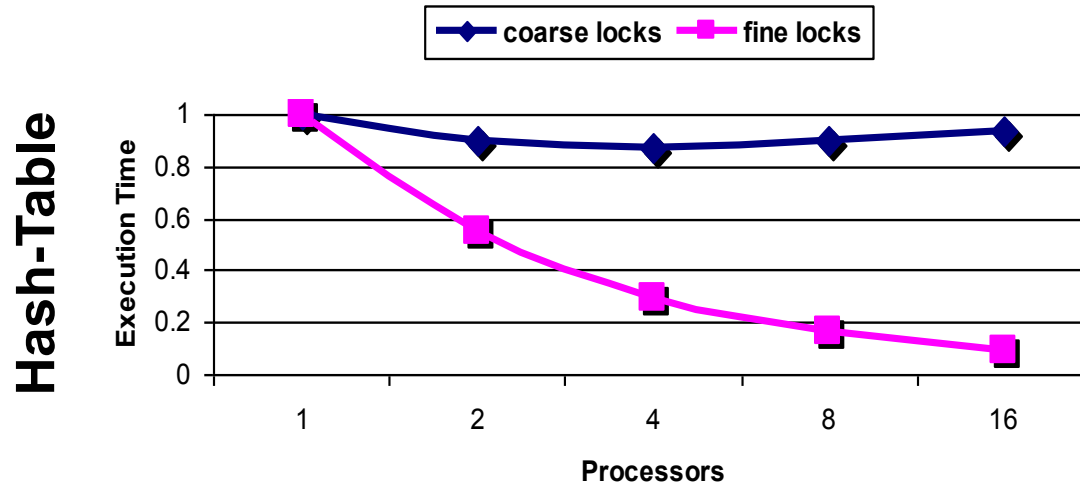
- Per-bucket locks
- *Problems?*

Locking overheads

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

# Performance: Locks

---



# Concurrency Control

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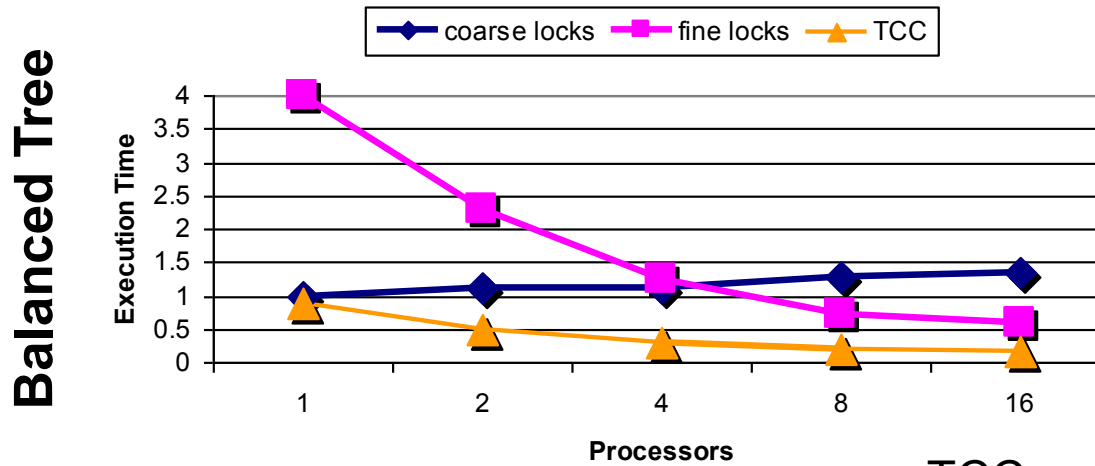
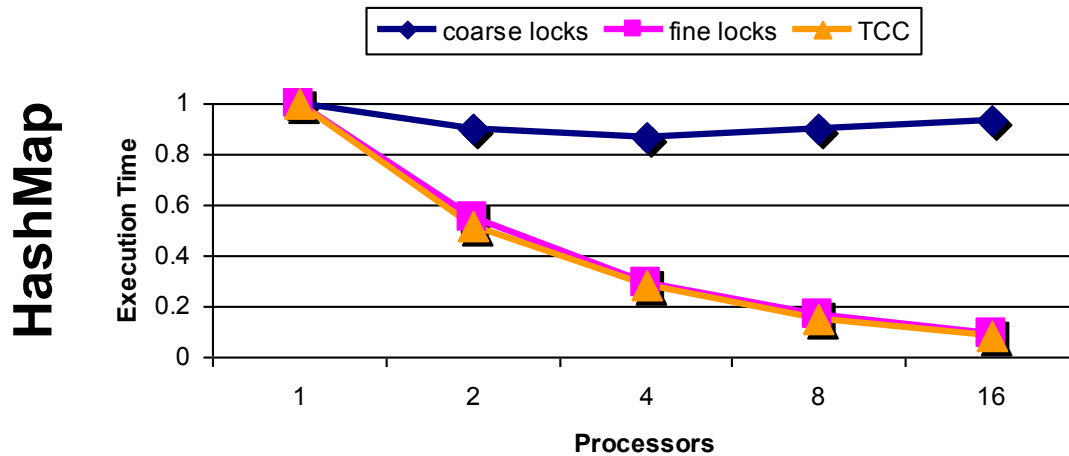
- Declarative synchronization
  - Programmers says what but not how
  - No declaration or management of locks
- System implements synchronization
  - Typically through speculation
  - Performance hit only on conflicts (R-W or W-W)

# Advantages of TM

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- 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]

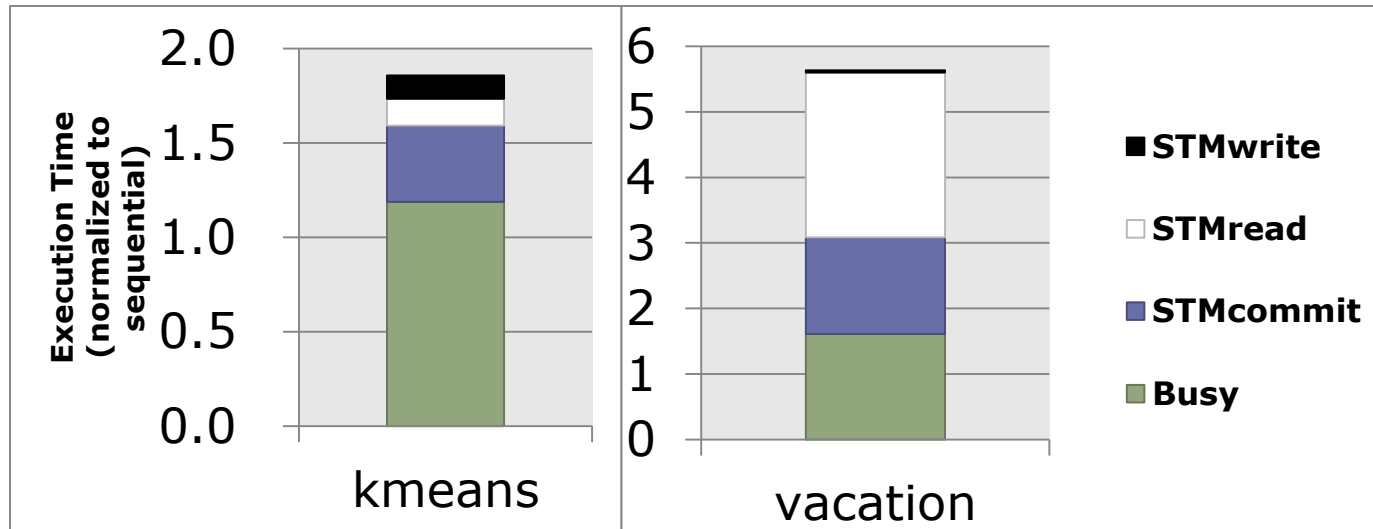
# TM Implementation Basics

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- 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)

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  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

---

Begin Xaction

Thread

Undo  
Log

X: 10

Memory

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Memory

Write X ← 15

Thread



Undo Log  
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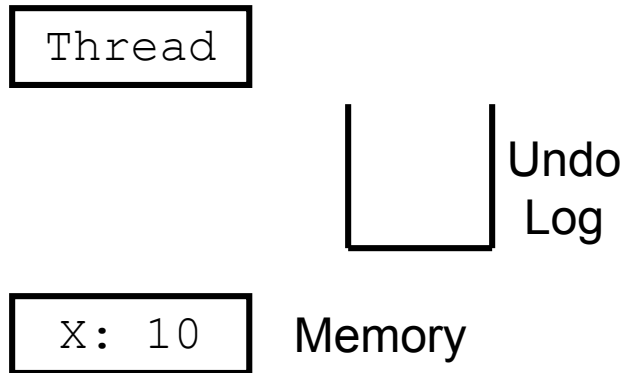
X: 15

Memory

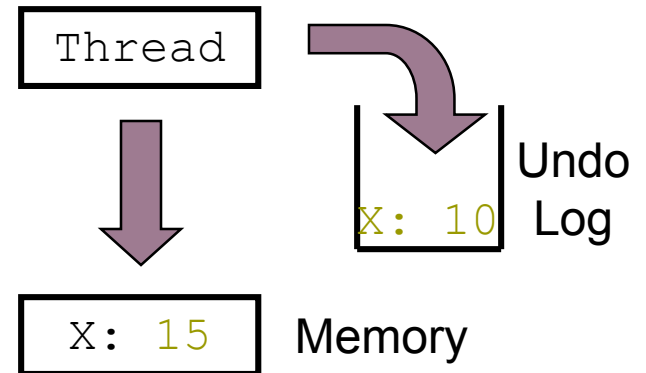


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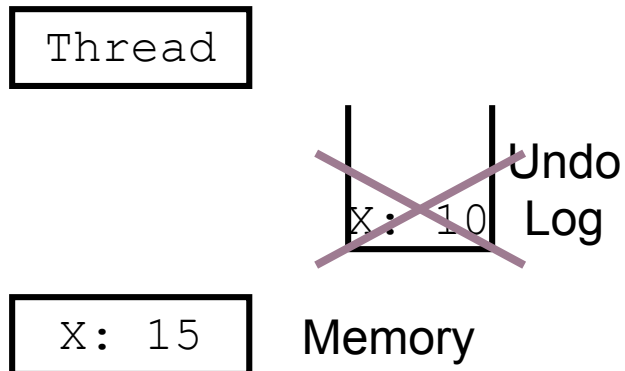
## Begin Xaction



## Write X ← 15

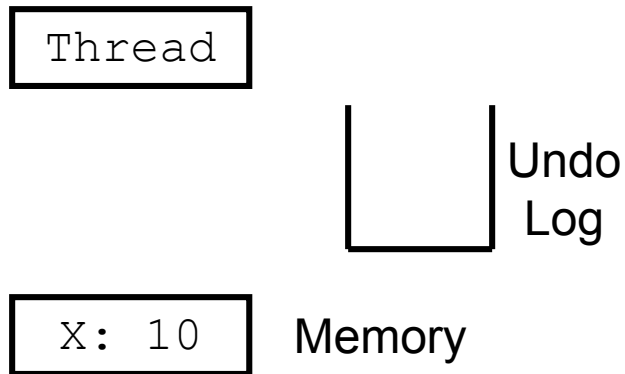


## Commit Xaction

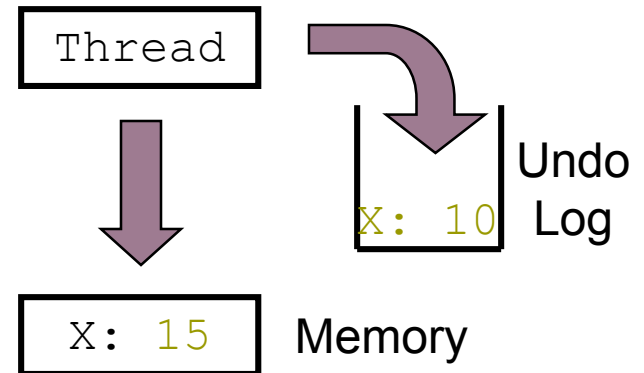


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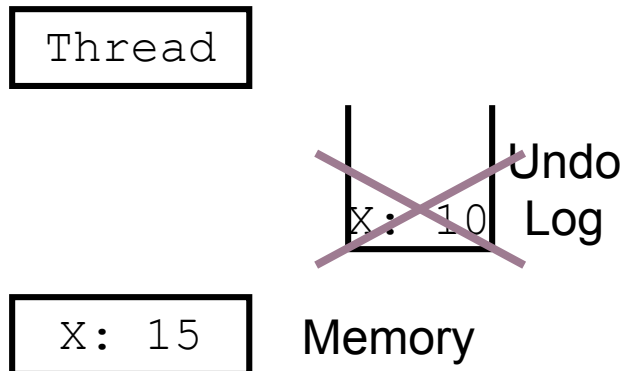
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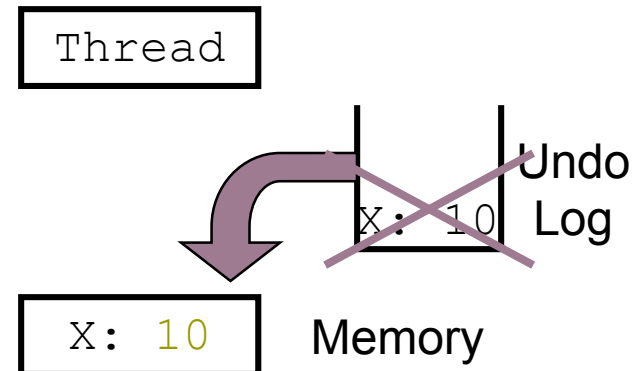
## Write X ← 15



## Commit Xaction



## Abort Xaction



# Lazy Versioning Illustration

---

Begin Xaction

Thread

Write  
Buffer

X: 10

Memory

# Lazy Versioning Illustration

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Thread

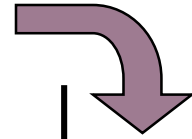
Write Buffer

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Memory

Write X ← 15

Thread



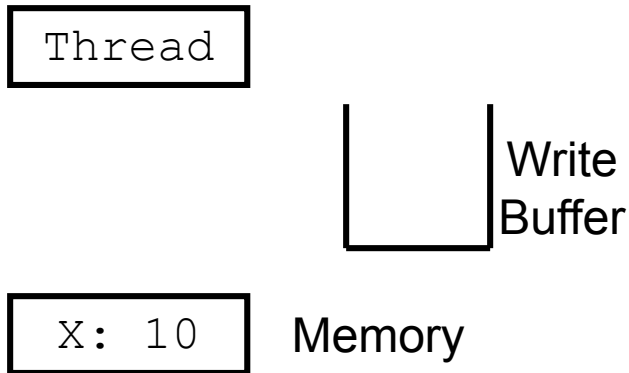
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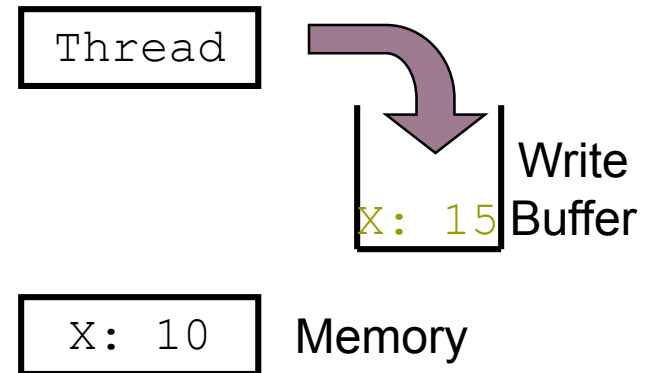
Memory

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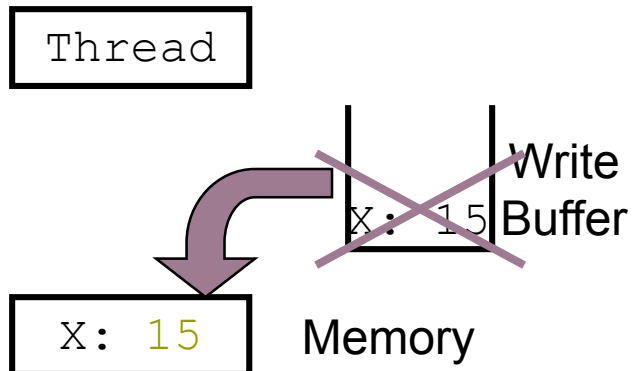
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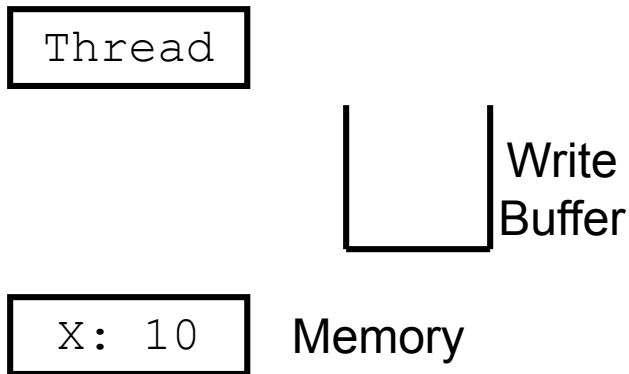


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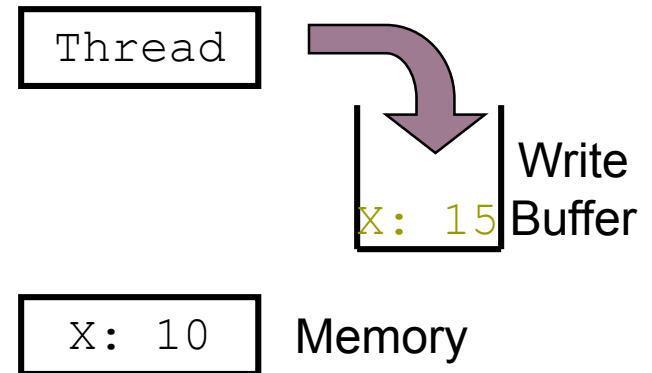


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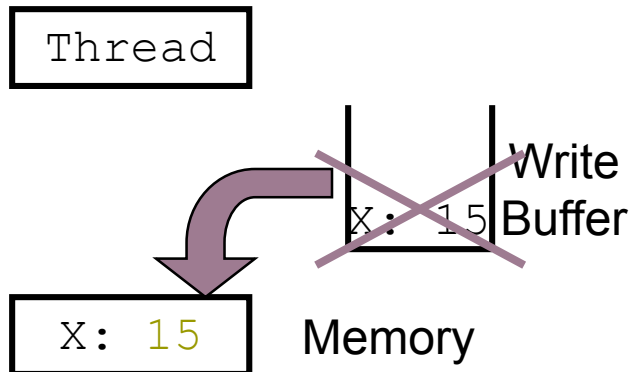
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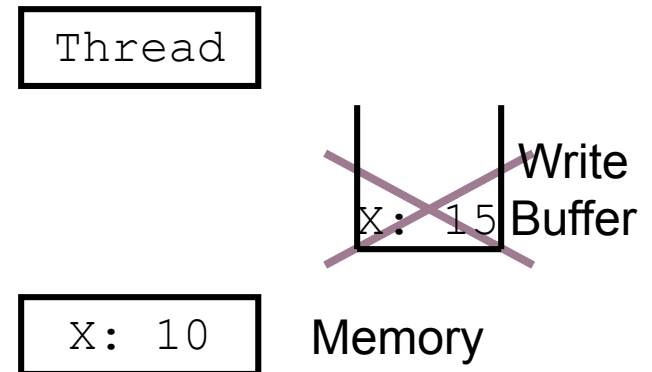
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# Conflict Detection

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- 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
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## 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



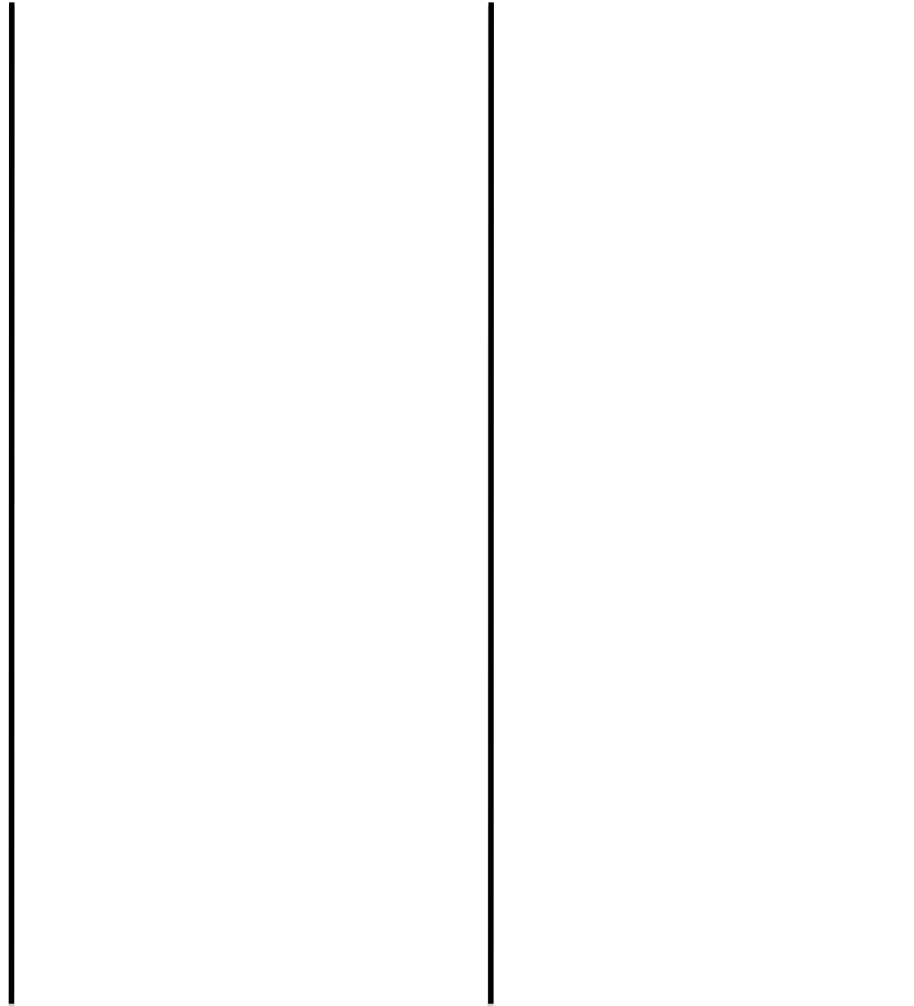
# Pessimistic Detection Illustration

---

Case 1

TIME  
↓

Success



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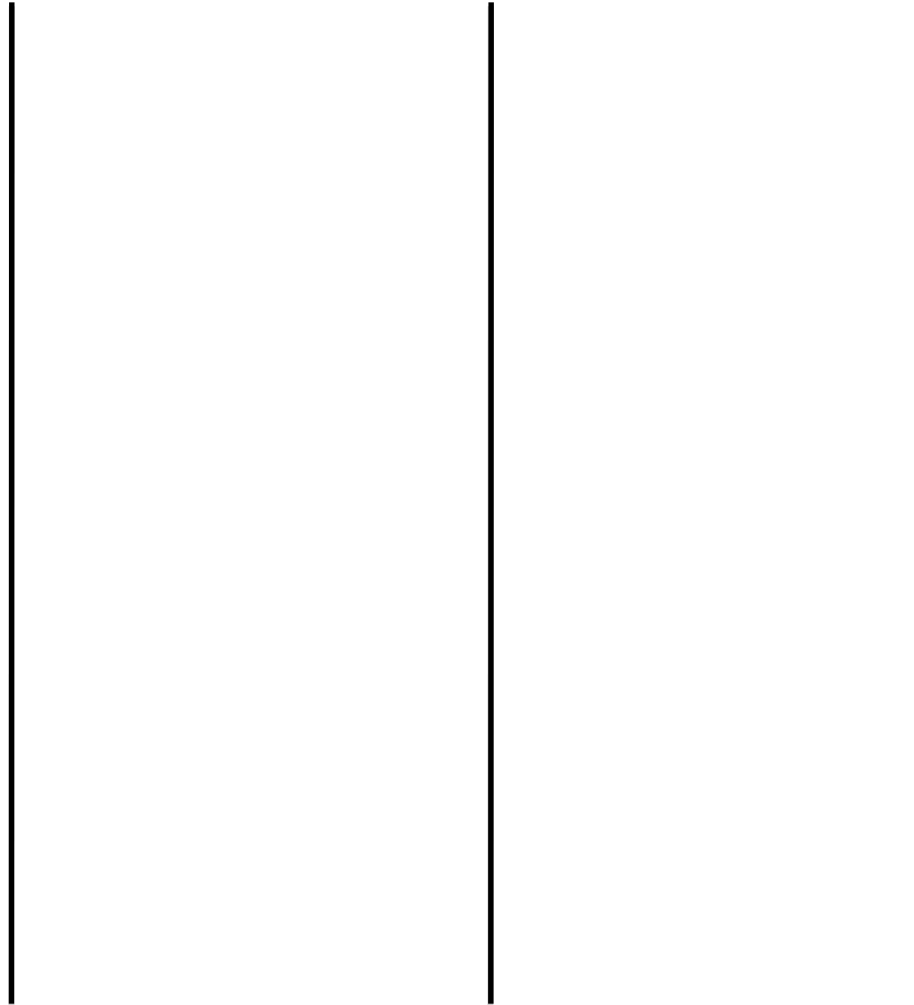
Case 1

X0

X1

TIME  
↓

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# Pessimistic Detection Illustration

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X0

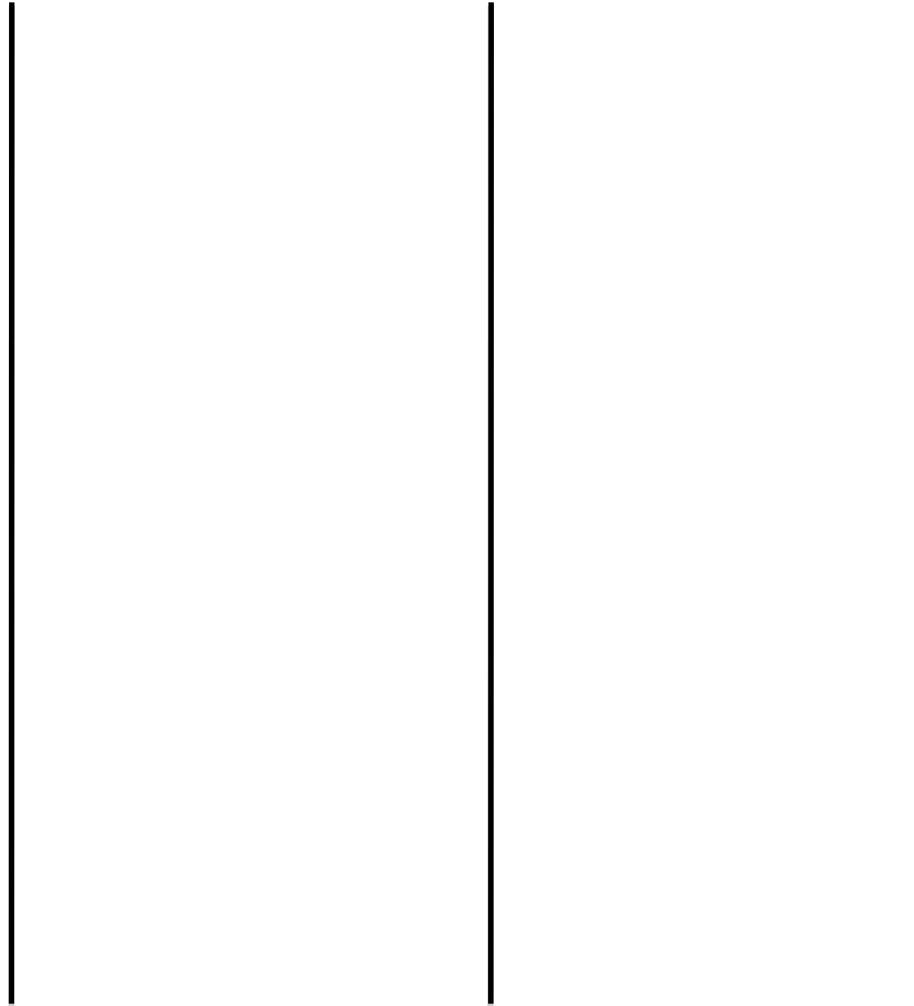


X1



Success

TIME  
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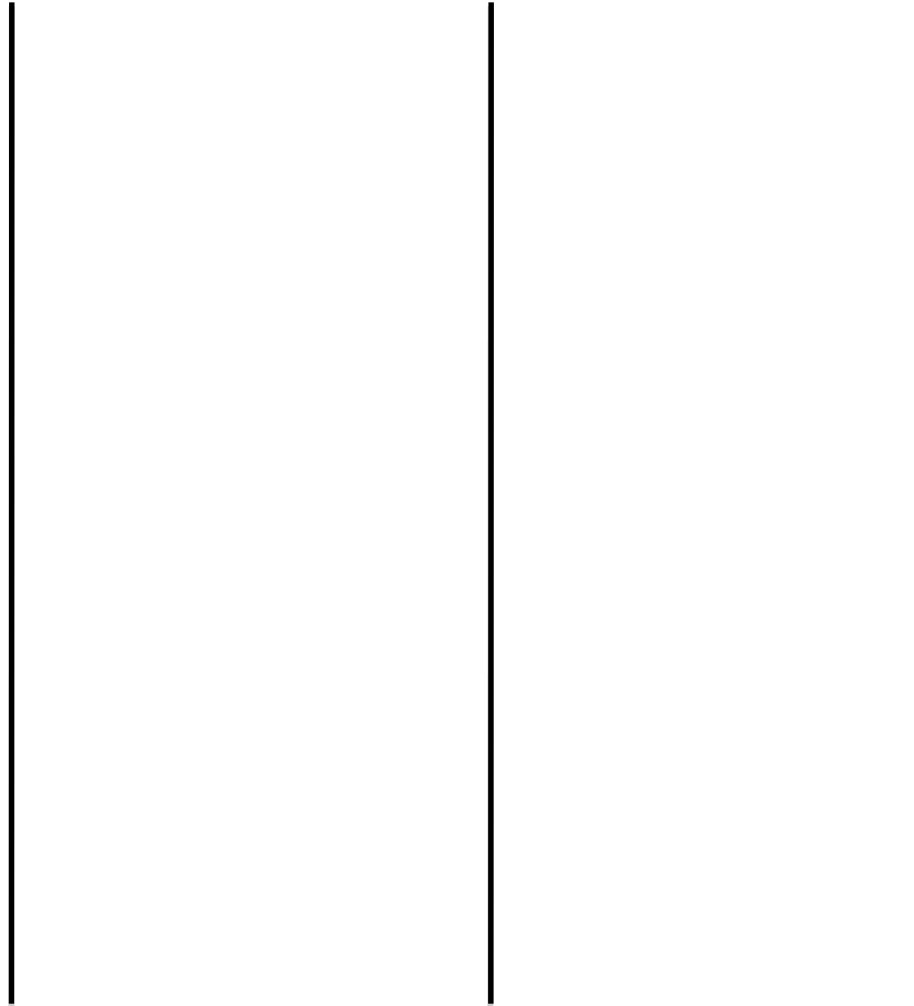
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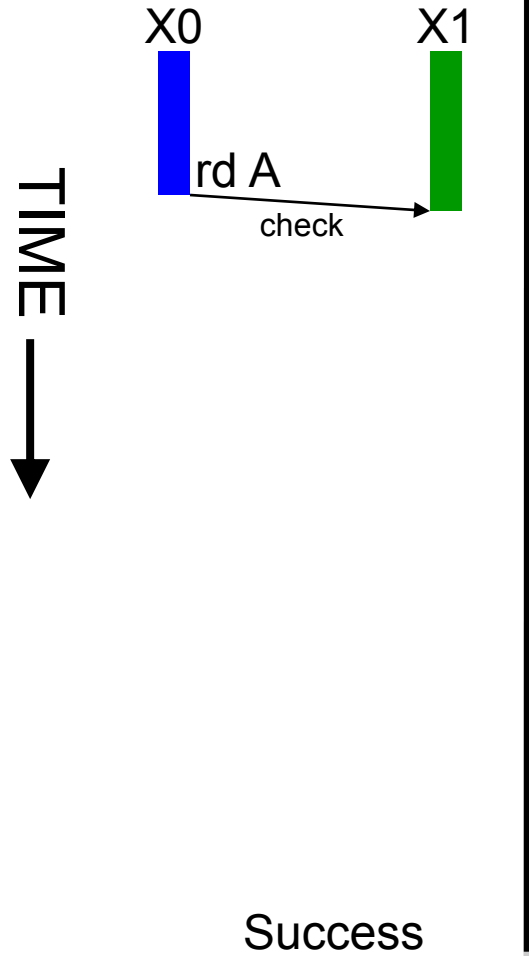
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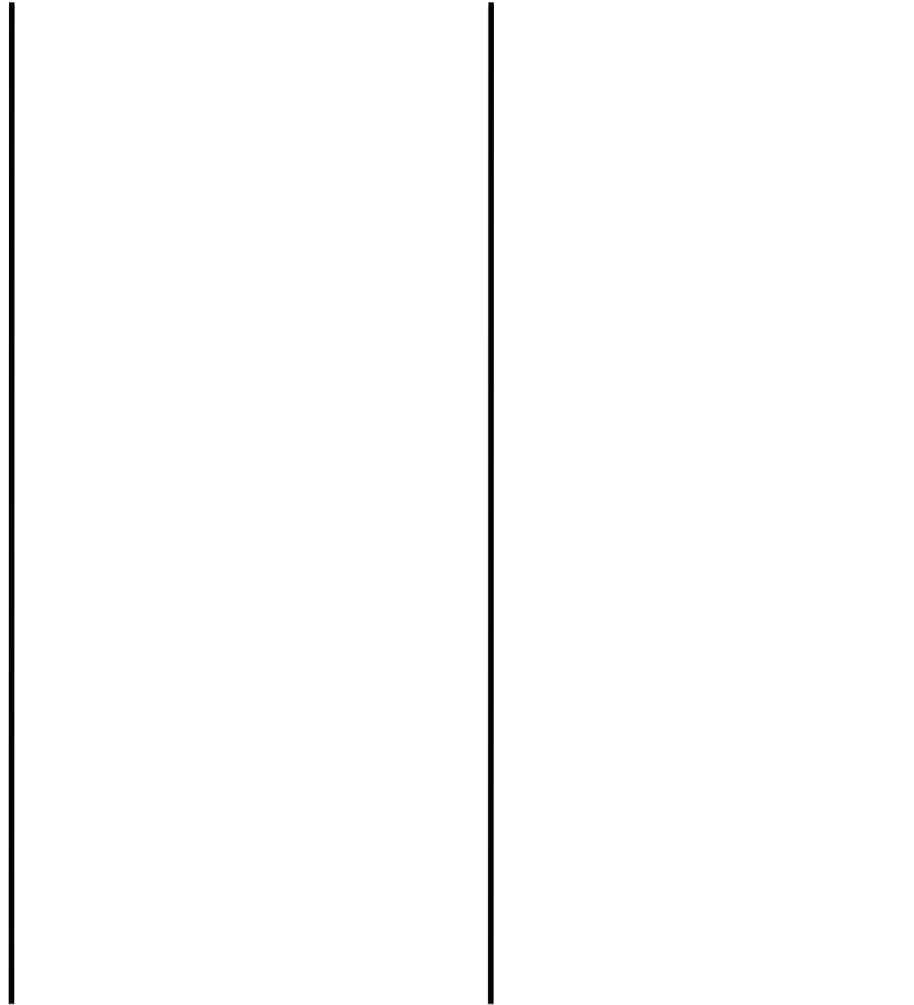
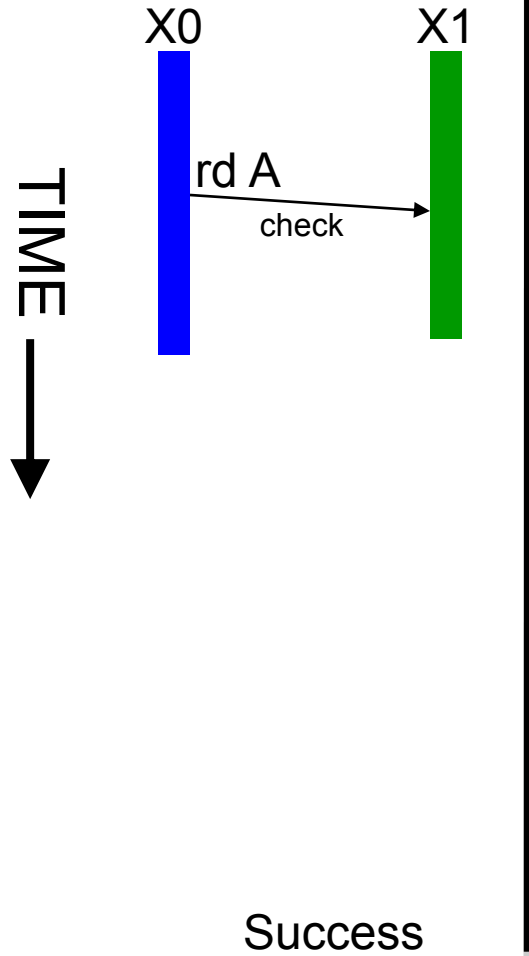
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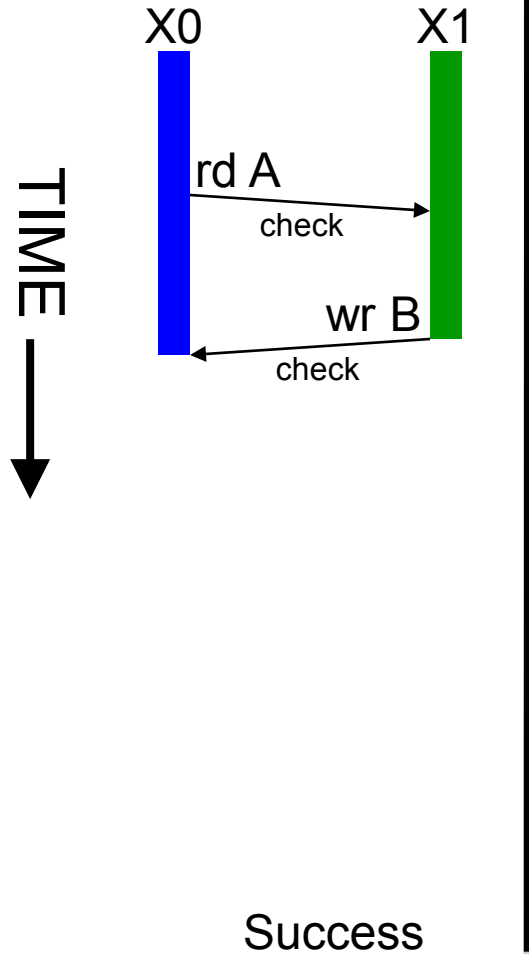
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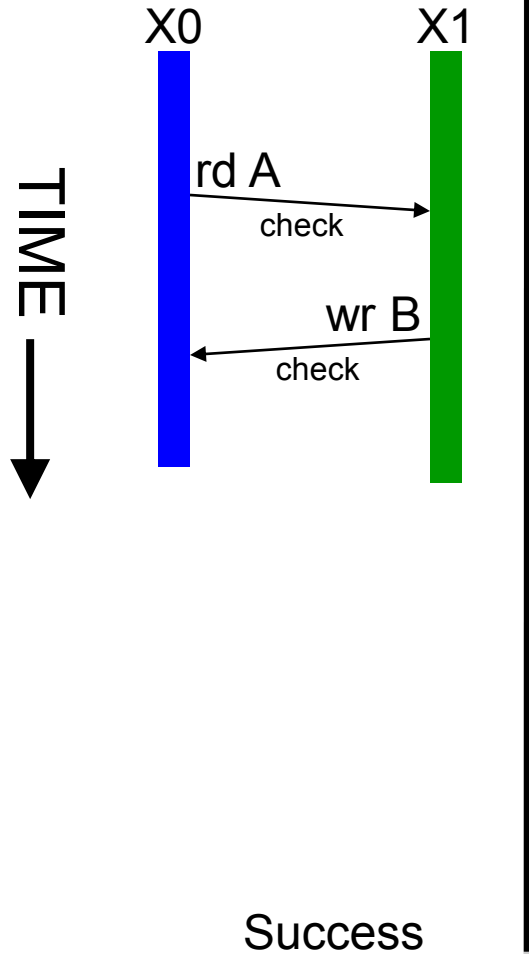
Case 1



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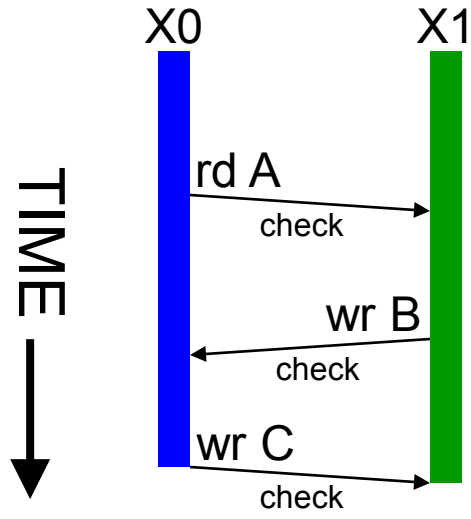




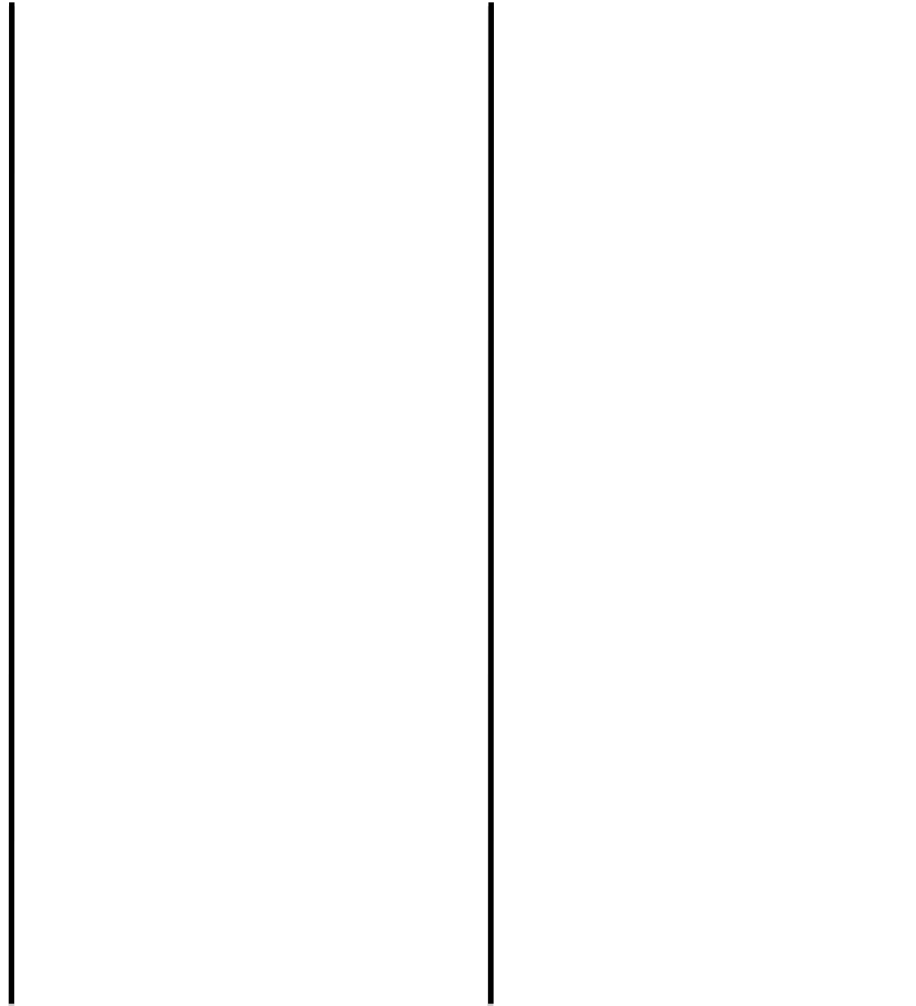
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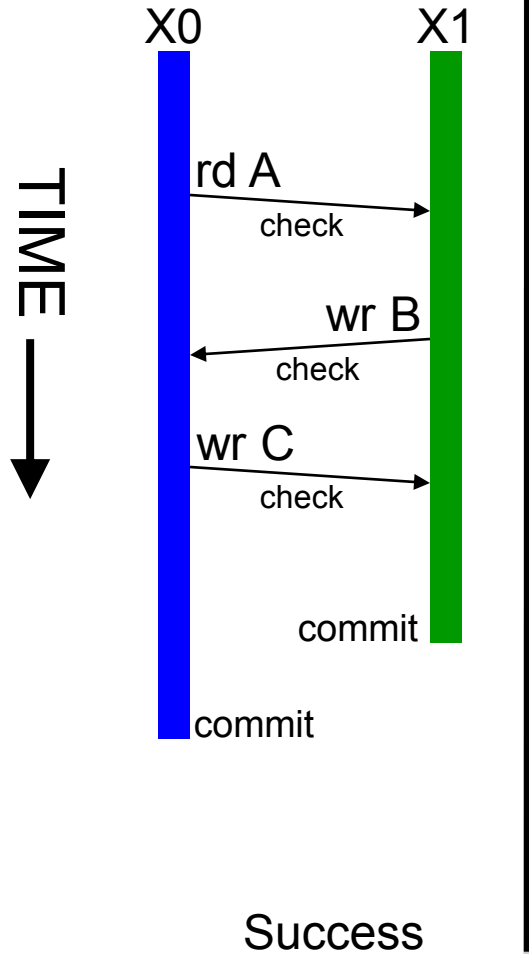
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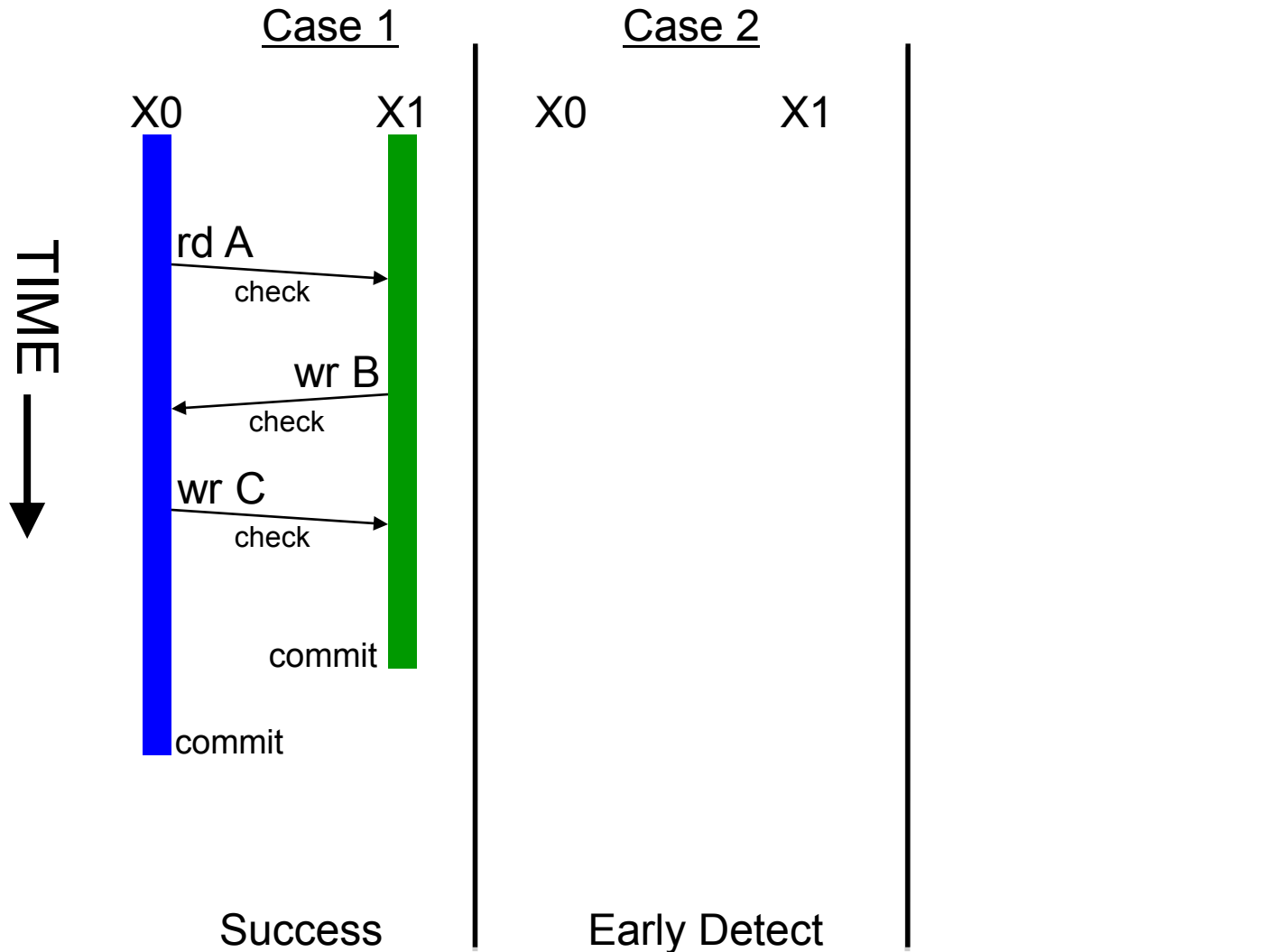
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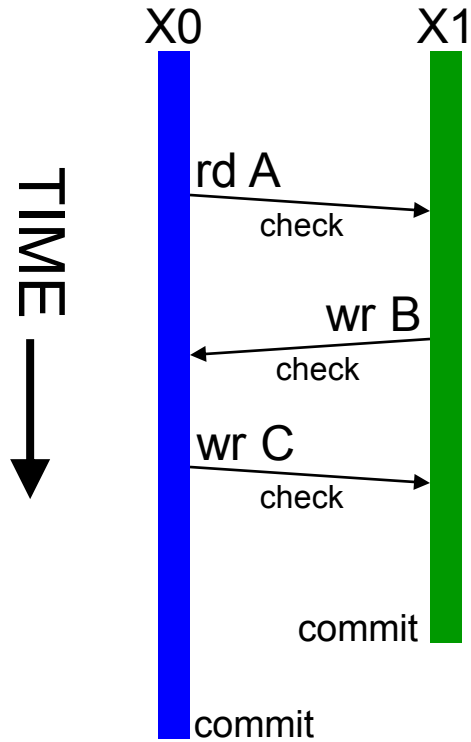


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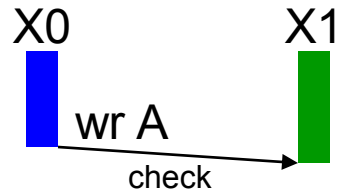
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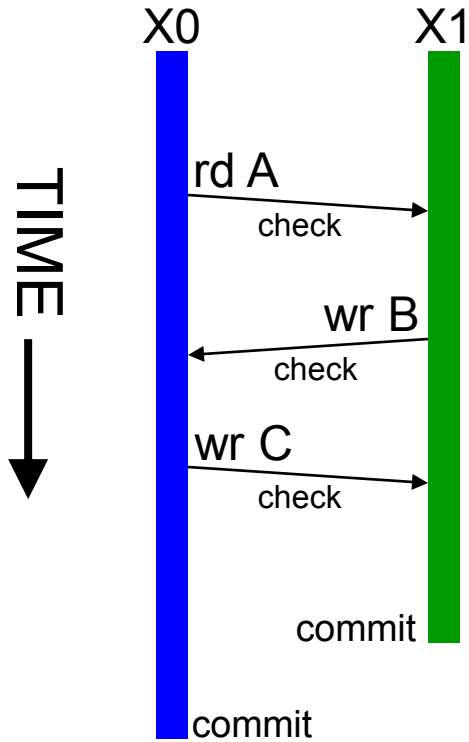
Case 2



Early Detect

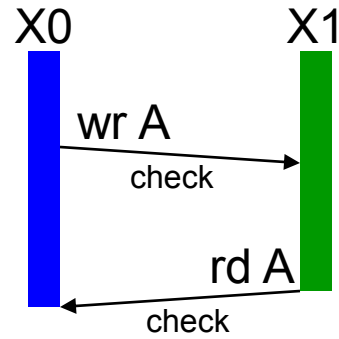
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Success

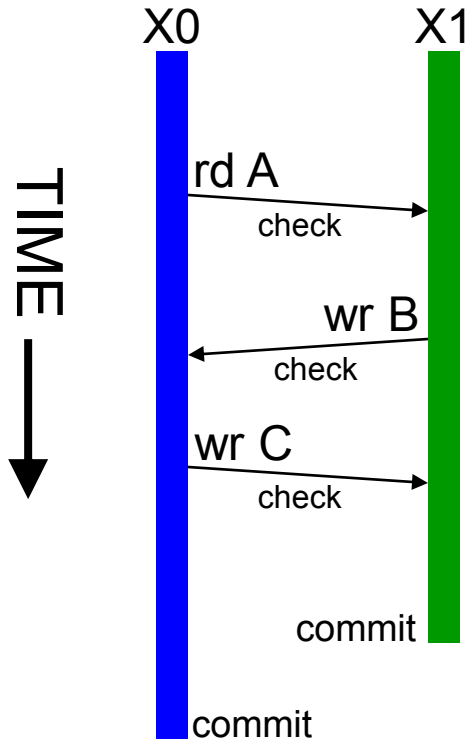
Case 2



Early Detect

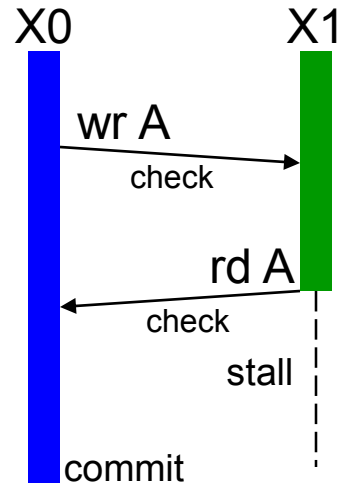
# Pessimistic Detection Illustration

Case 1



Success

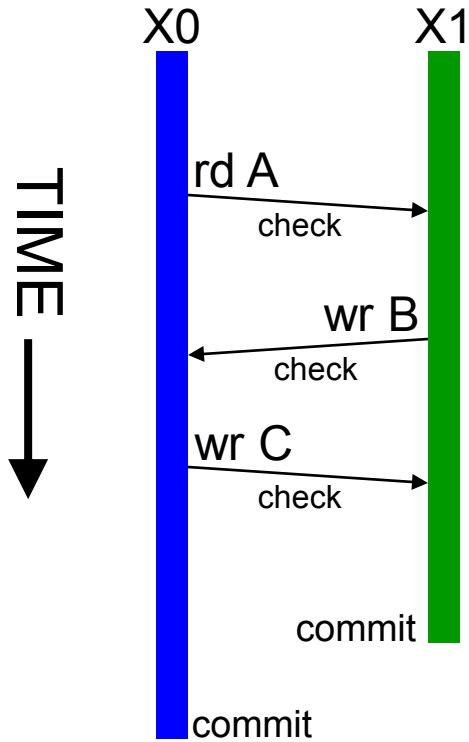
Case 2



Early Detect

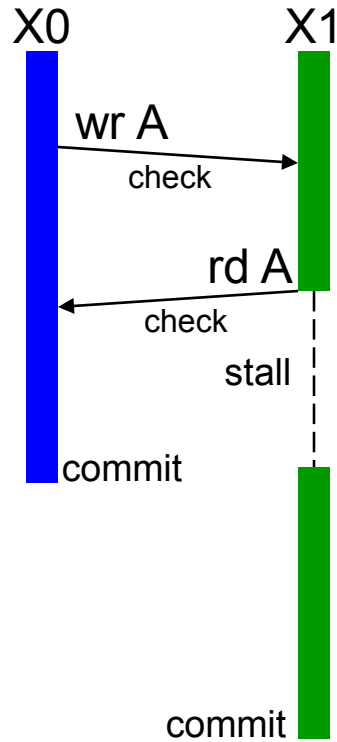
# Pessimistic Detection Illustration

Case 1



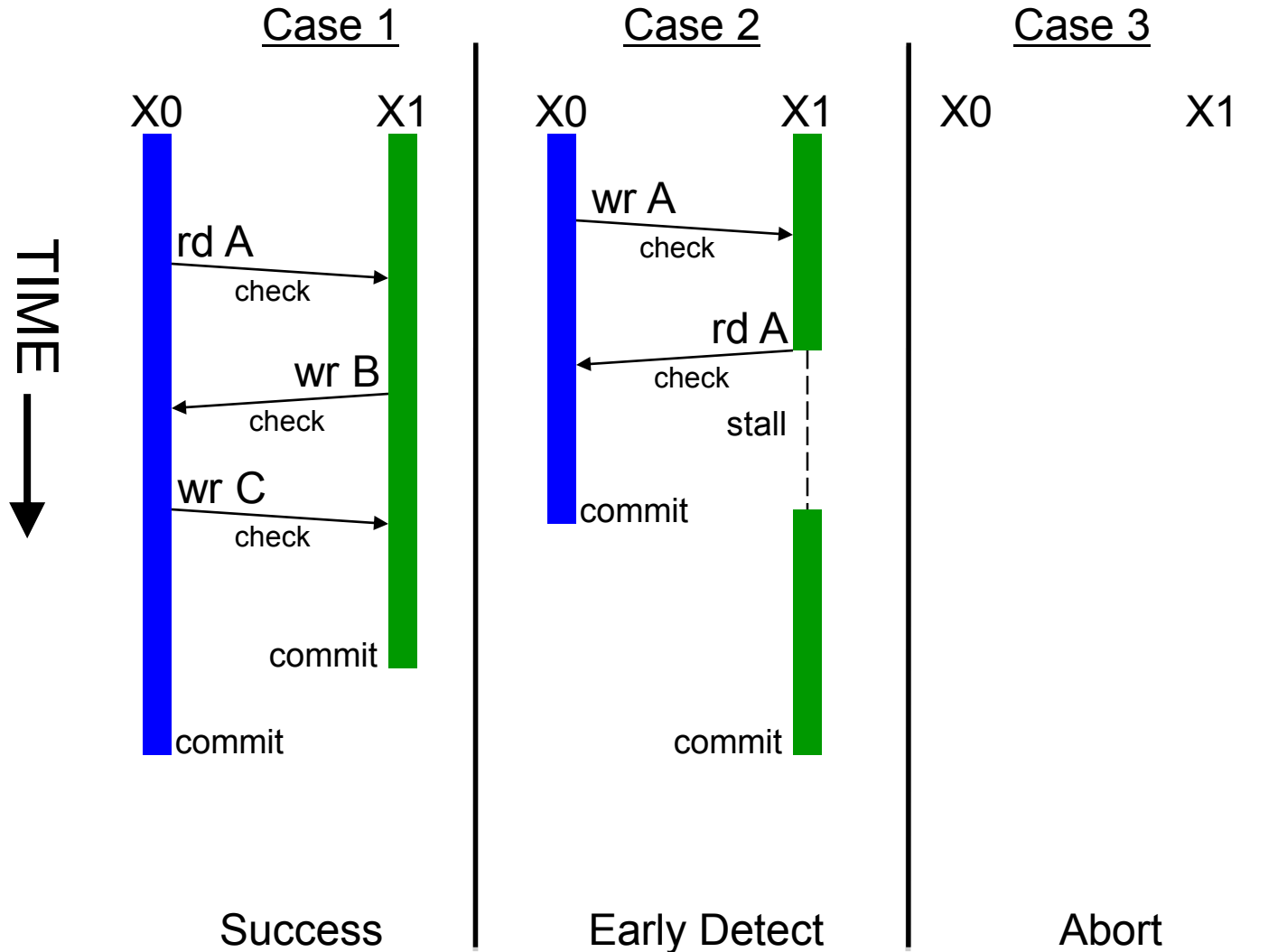
Success

Case 2



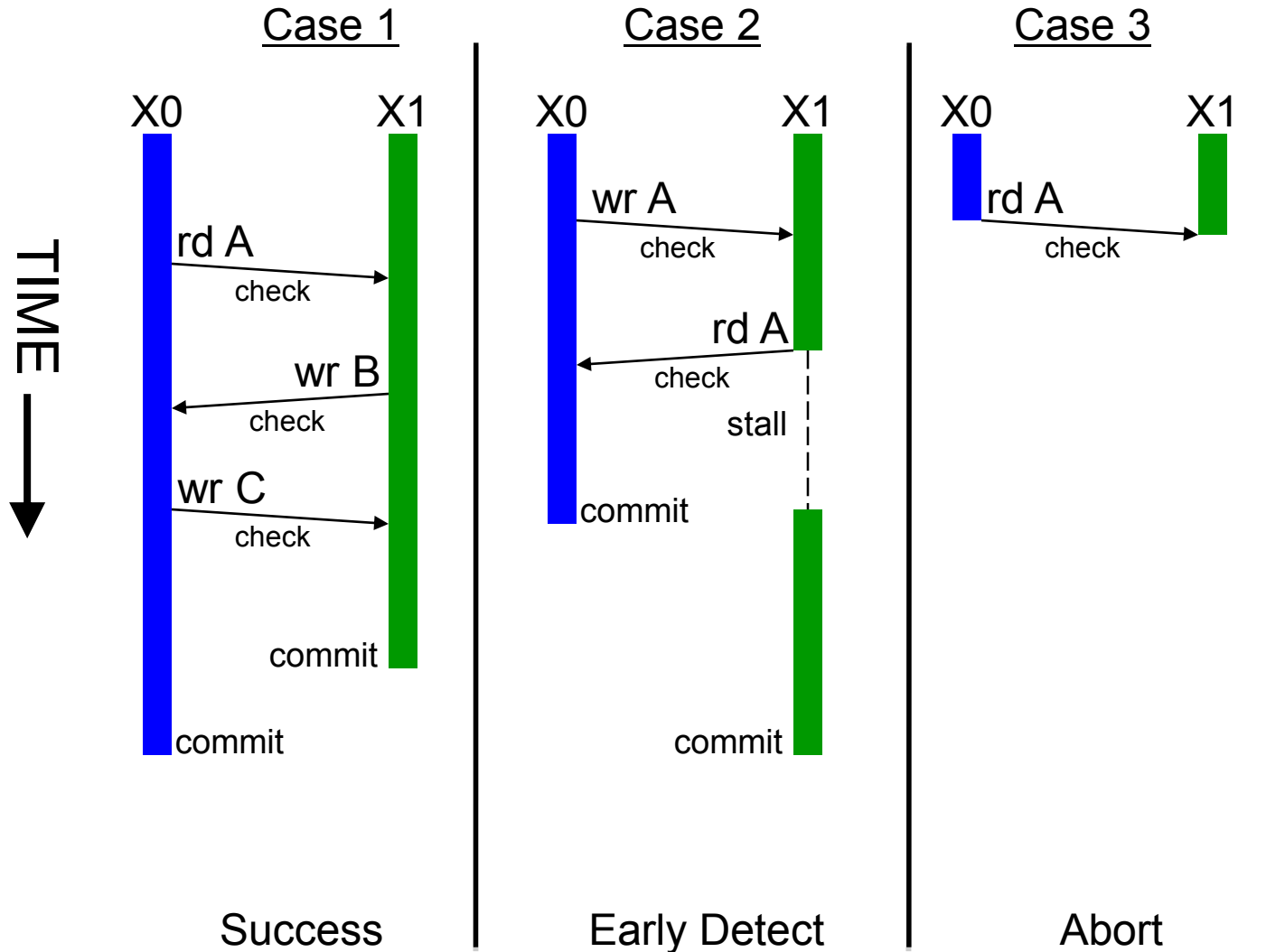
Early Detect

# Pessimistic Detection Illustration

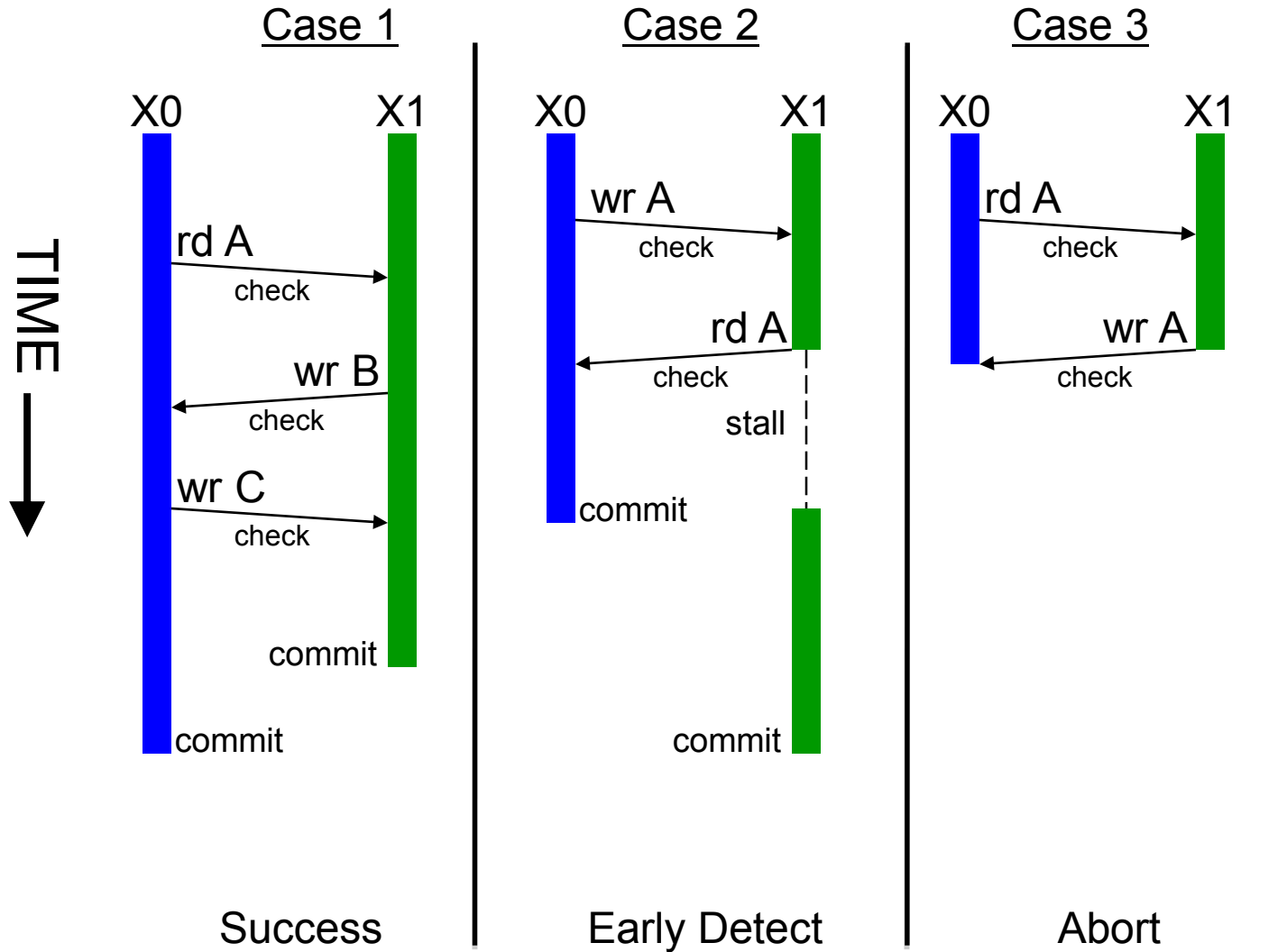




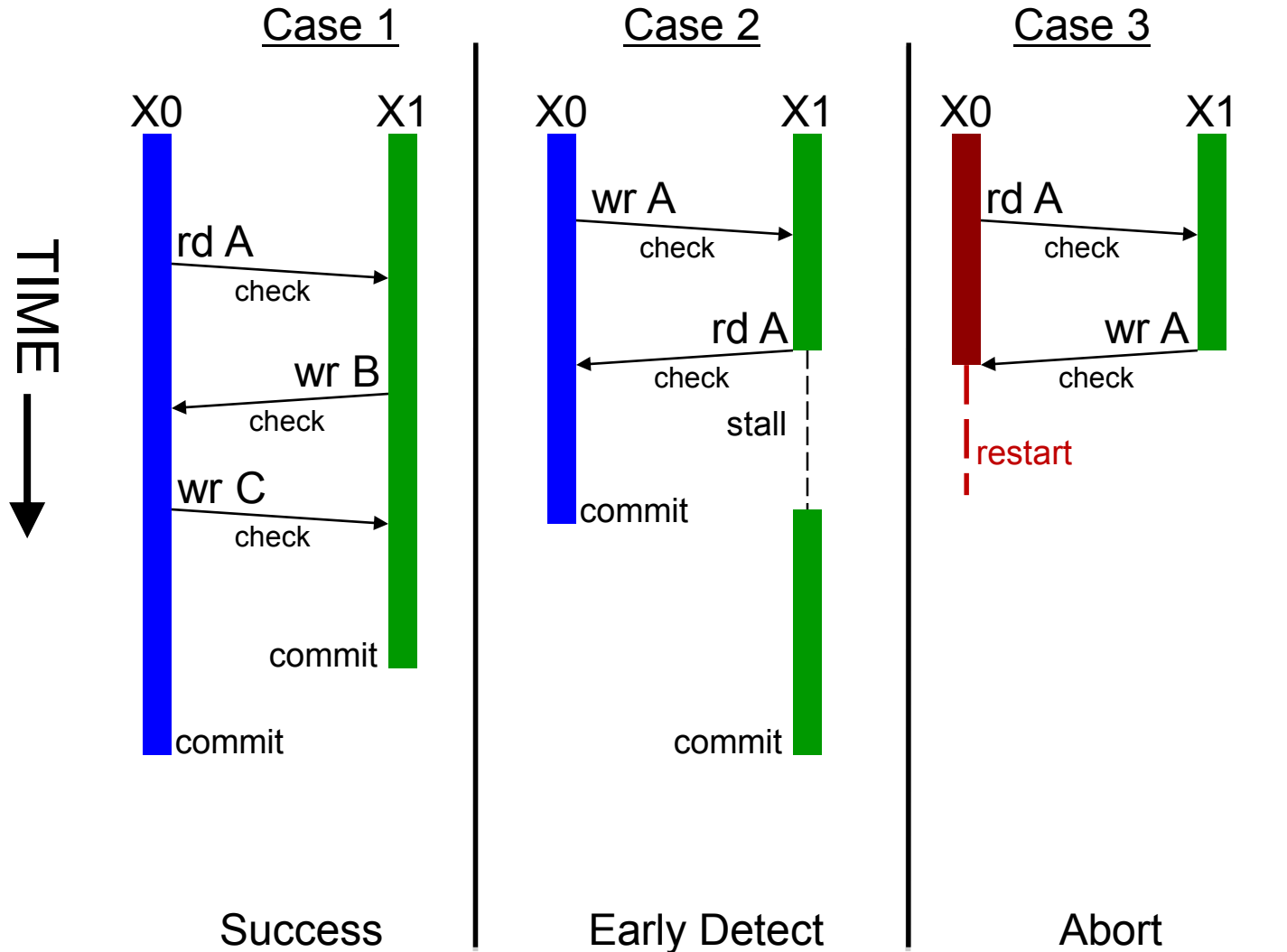
# Pessimistic Detection Illustration



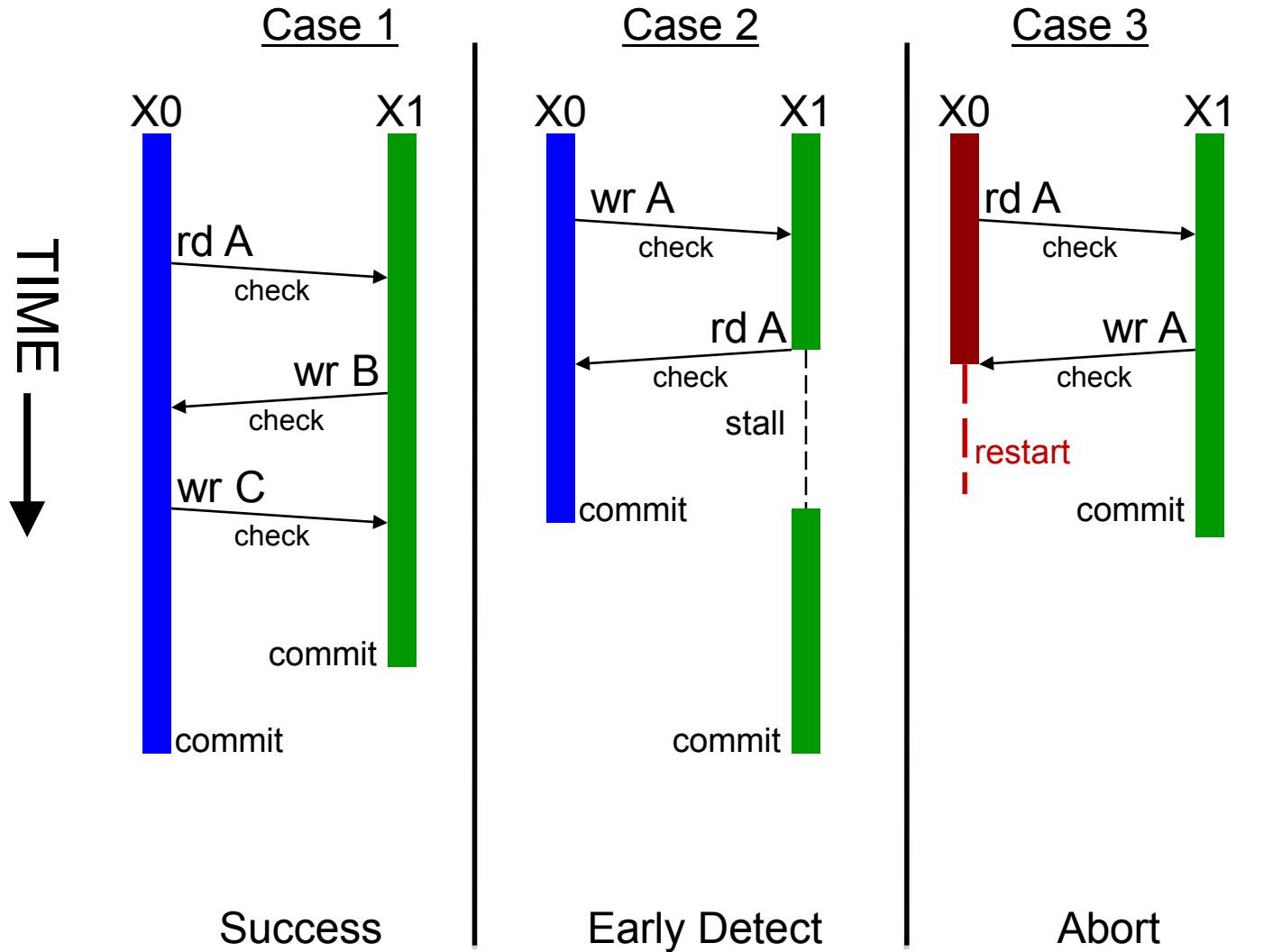
# Pessimistic Detection Illustration



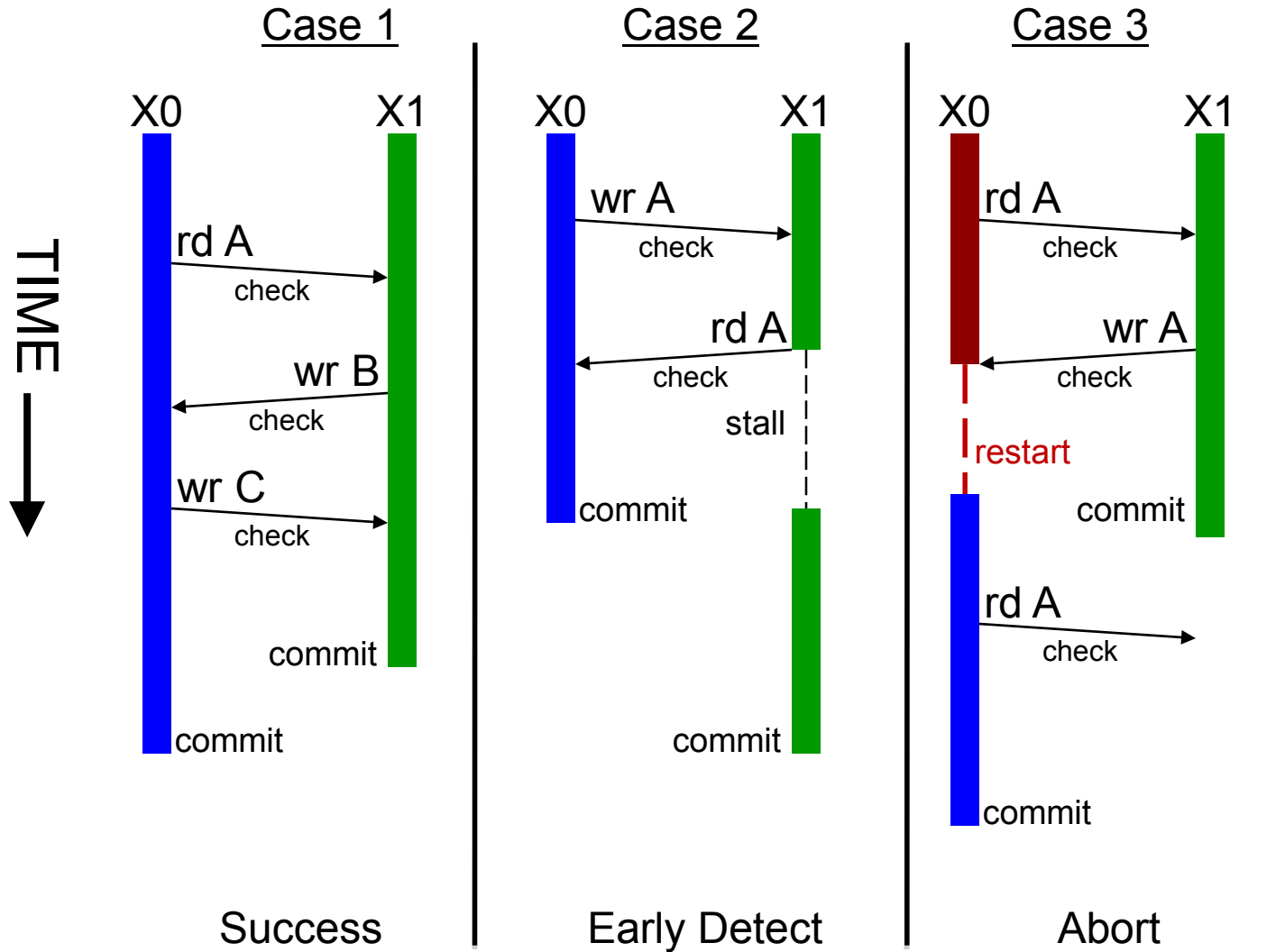
# Pessimistic Detection Illustration



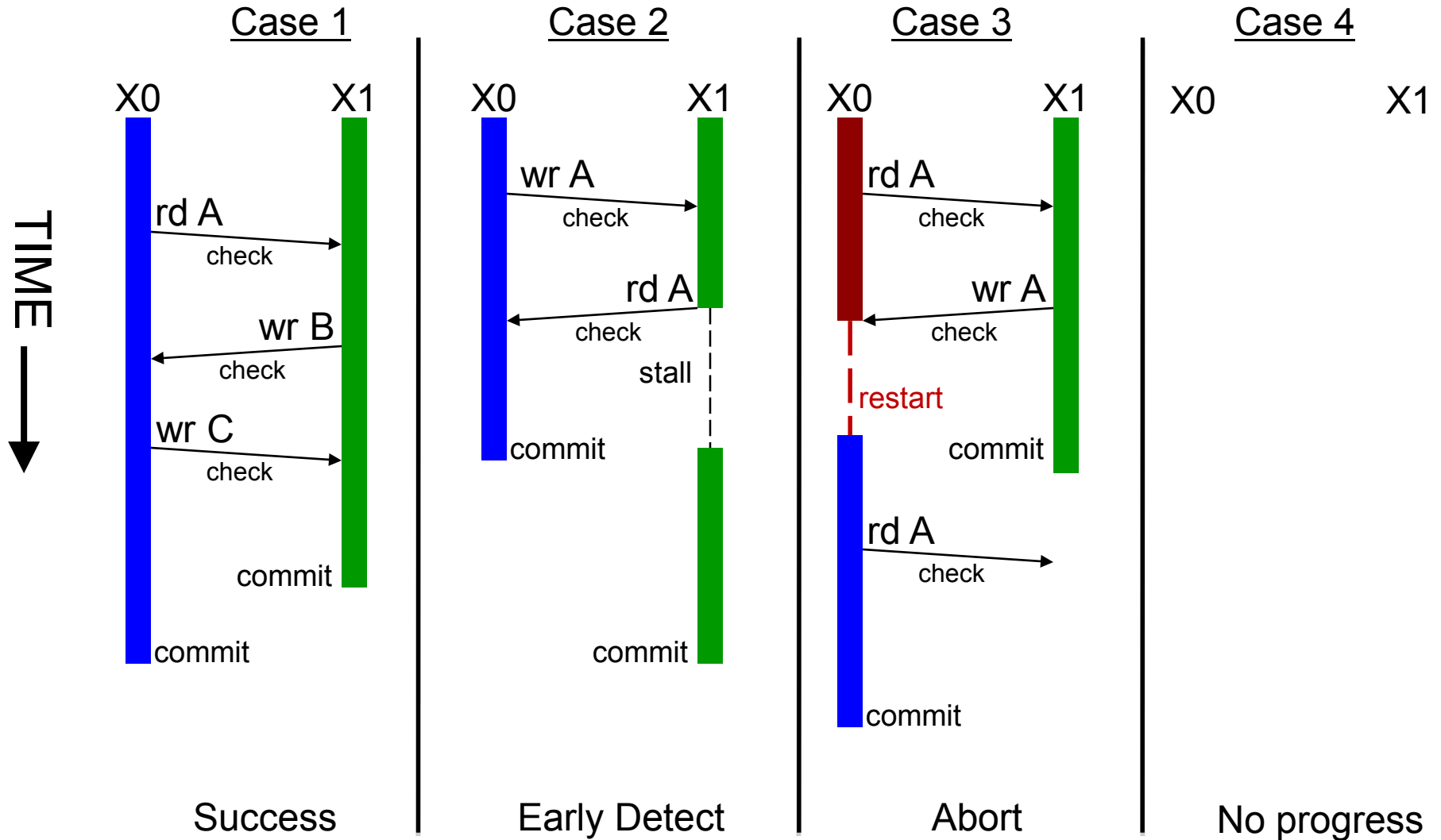
# Pessimistic Detection Illustration



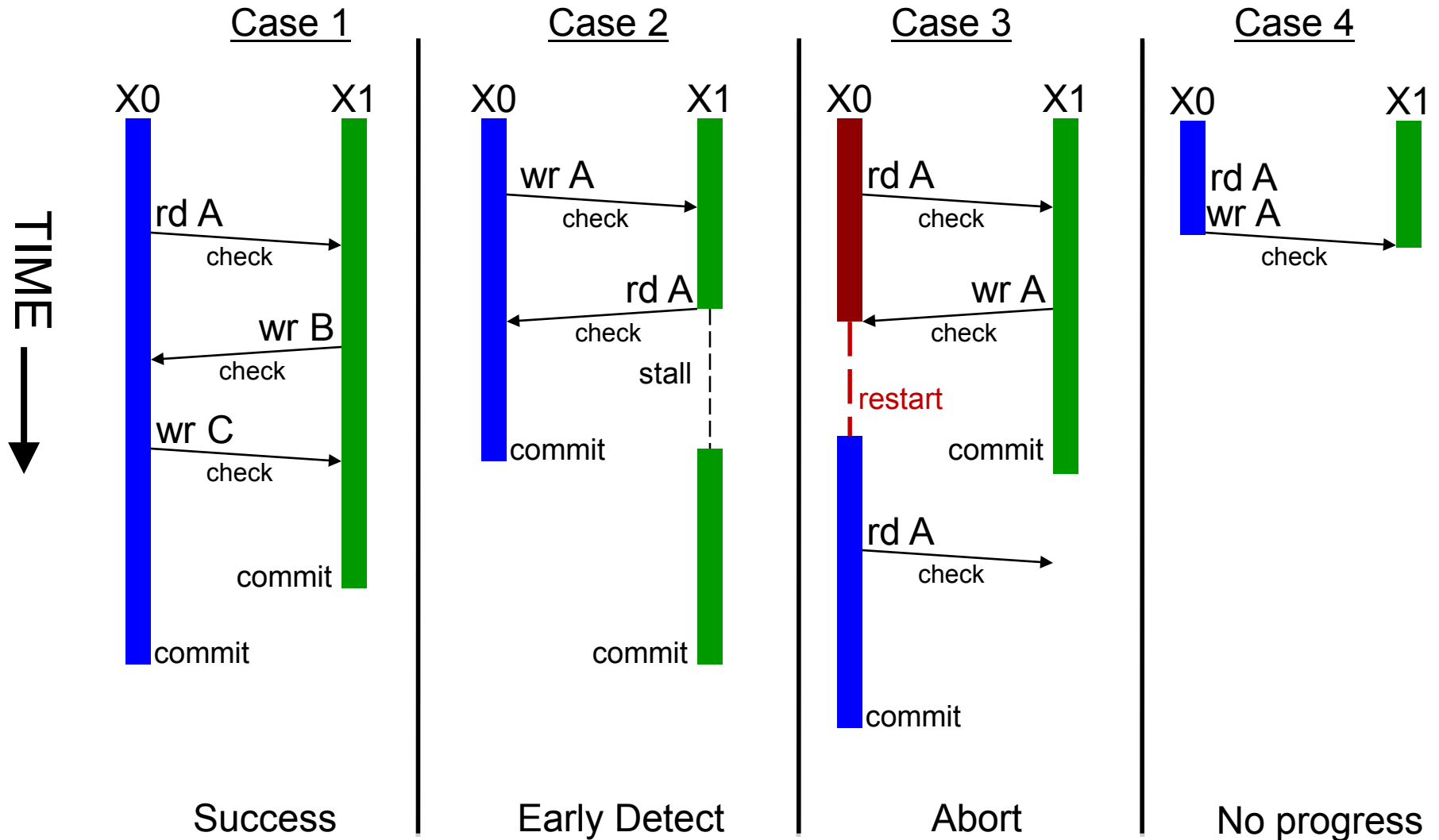
# Pessimistic Detection Illustration



# Pessimistic Detection Illustration

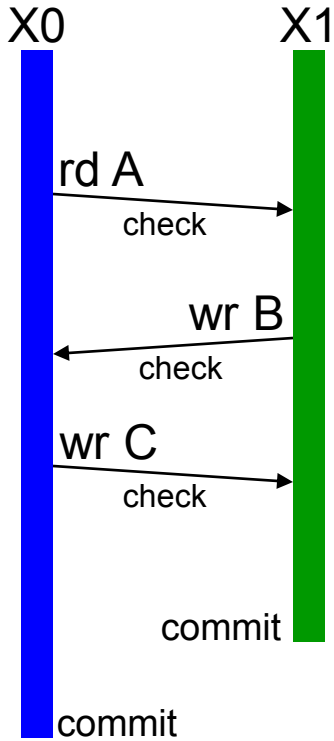


# Pessimistic Detection Illustration



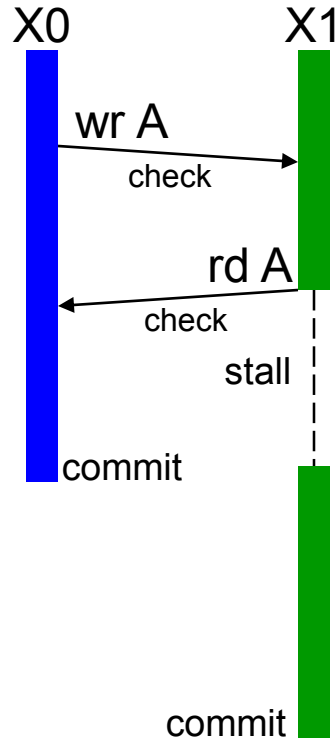
# Pessimistic Detection Illustration

Case 1



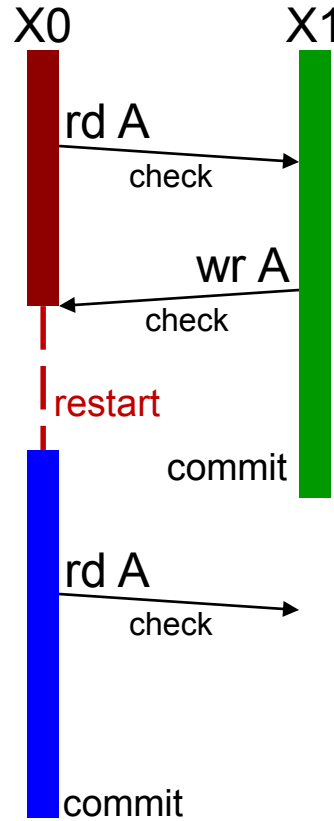
Success

Case 2



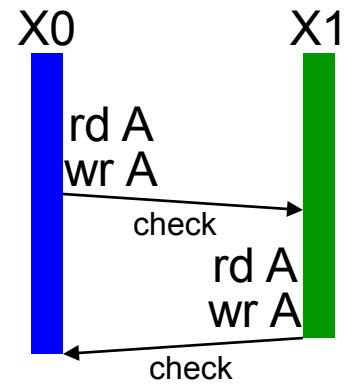
Early Detect

Case 3



Abort

Case 4

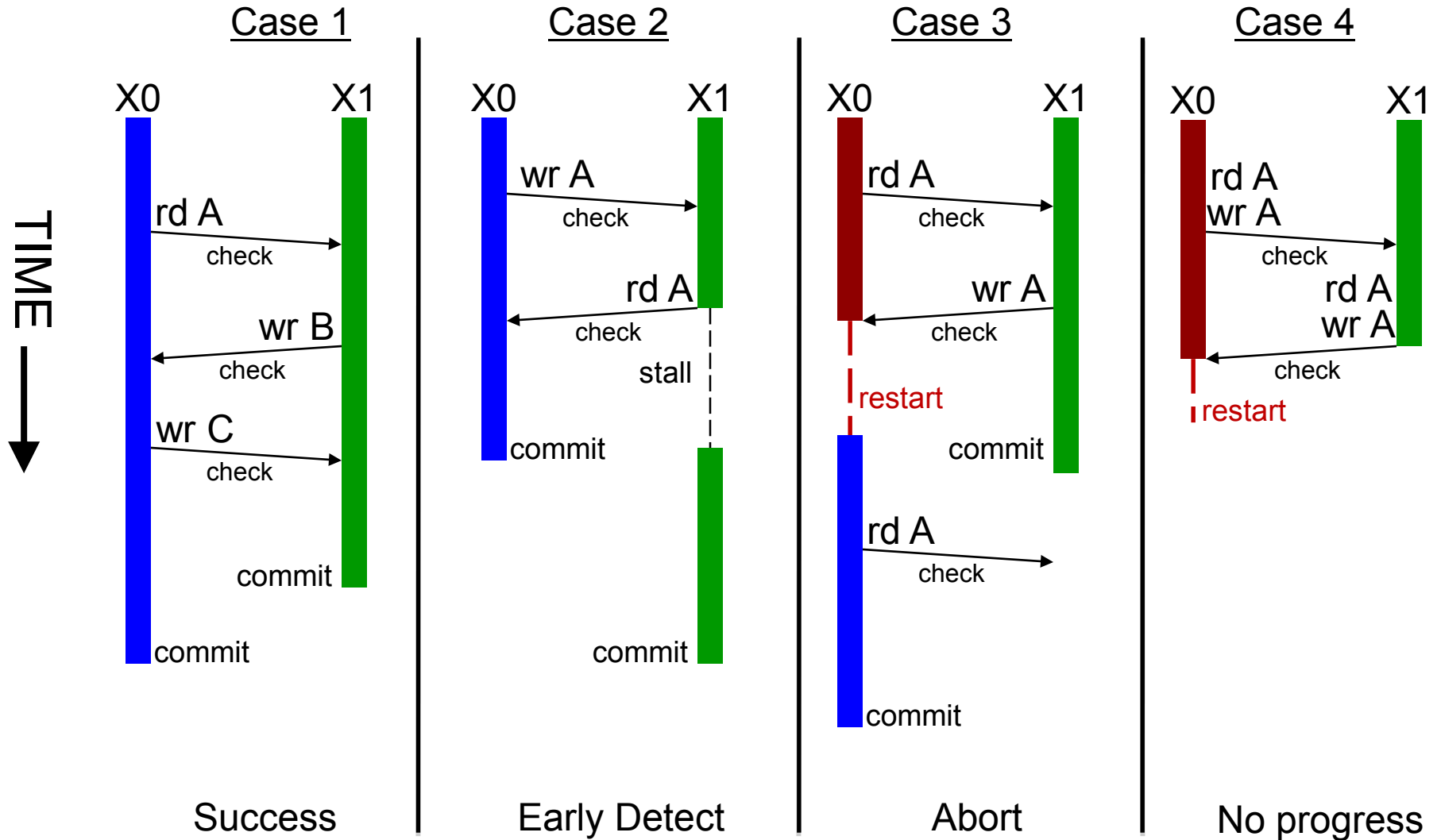


No progress

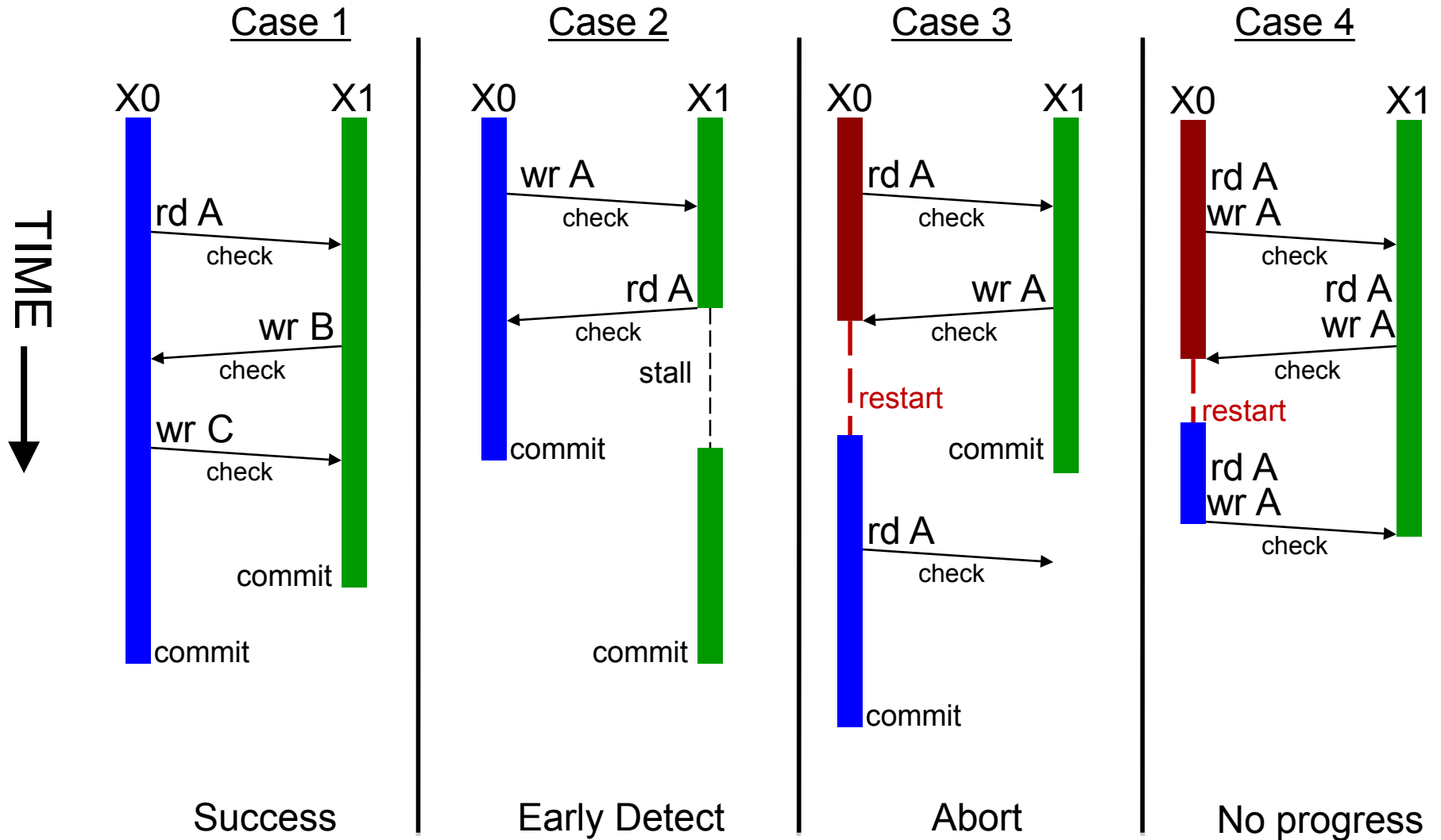
TIME  
↓



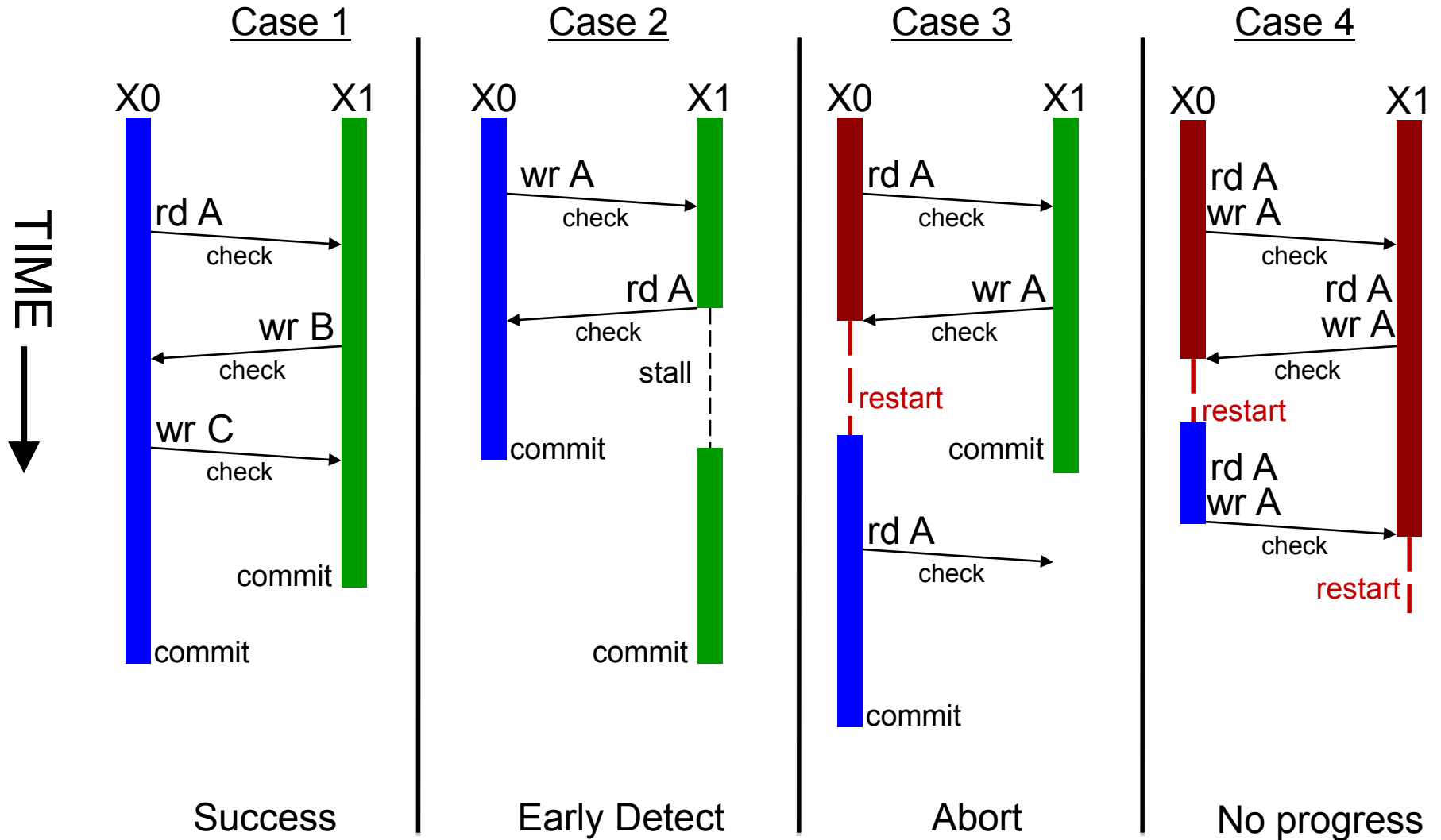
# Pessimistic Detection Illustration



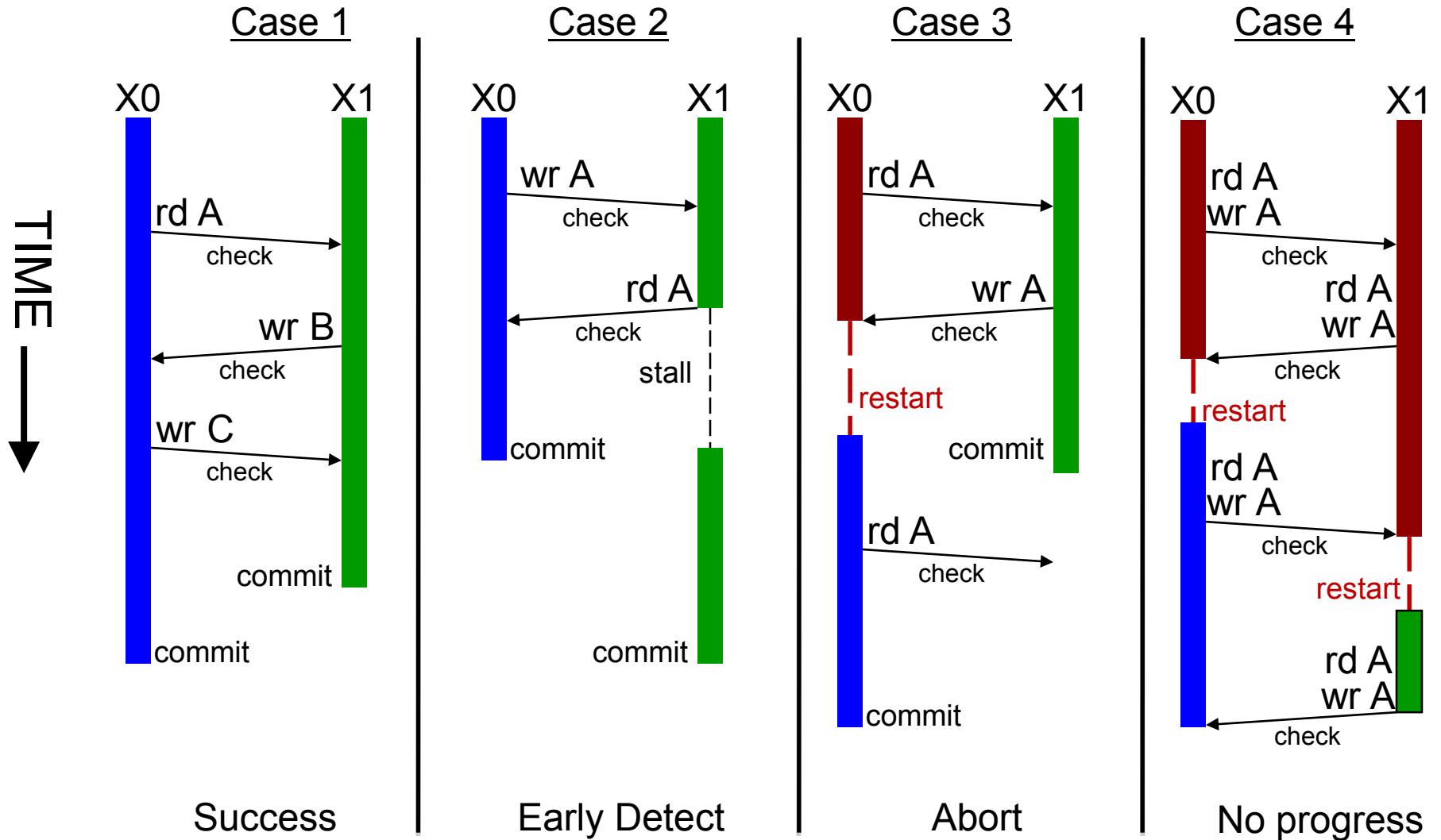
# Pessimistic Detection Illustration



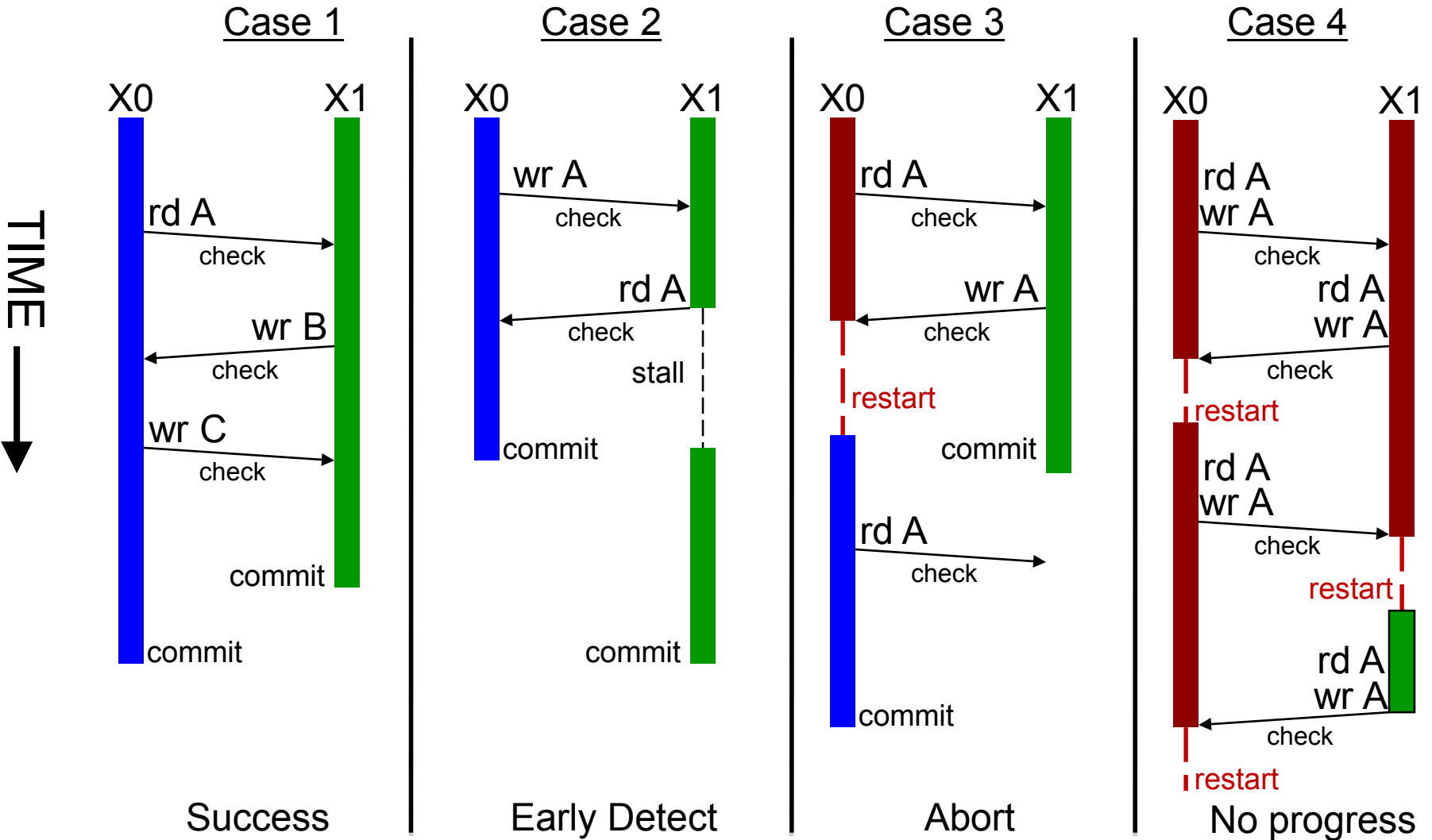
# Pessimistic Detection Illustration



# Pessimistic Detection Illustration



# Pessimistic Detection Illustration



# Conflict Detection (cont)

---

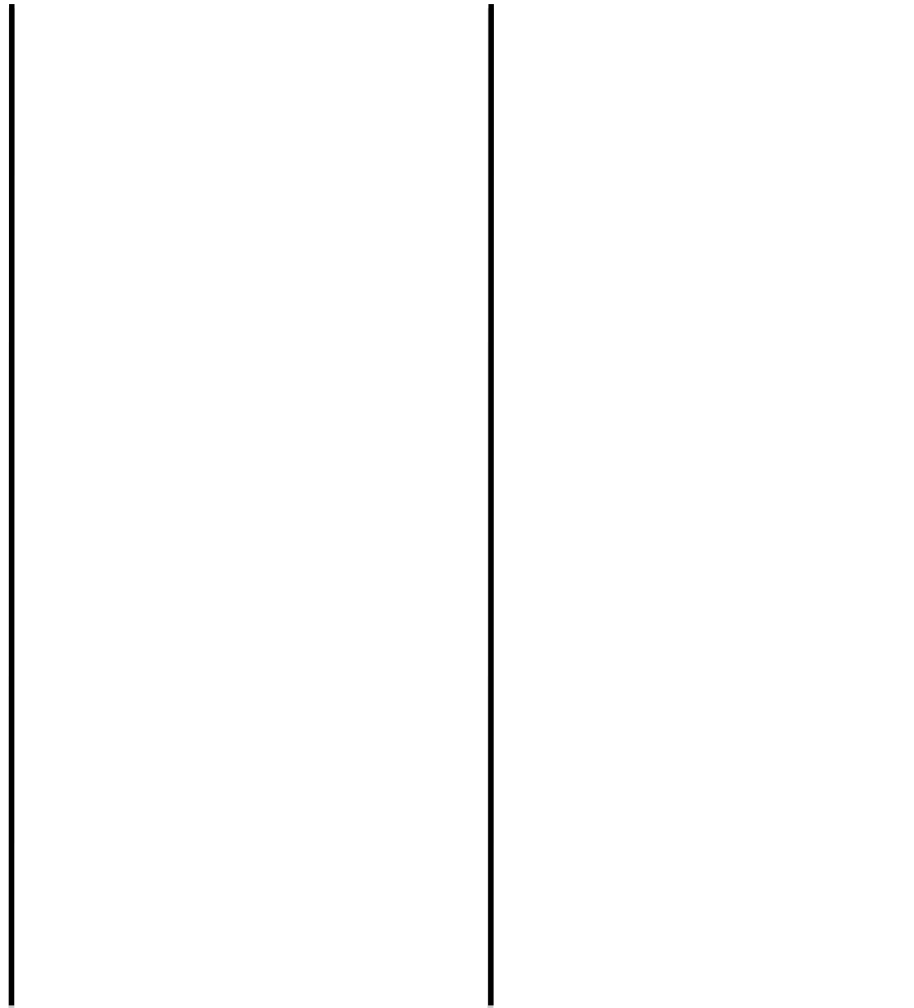
## 2. Optimistic detection

- 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

---

TIME  
↓



# Optimistic Detection Illustration

---

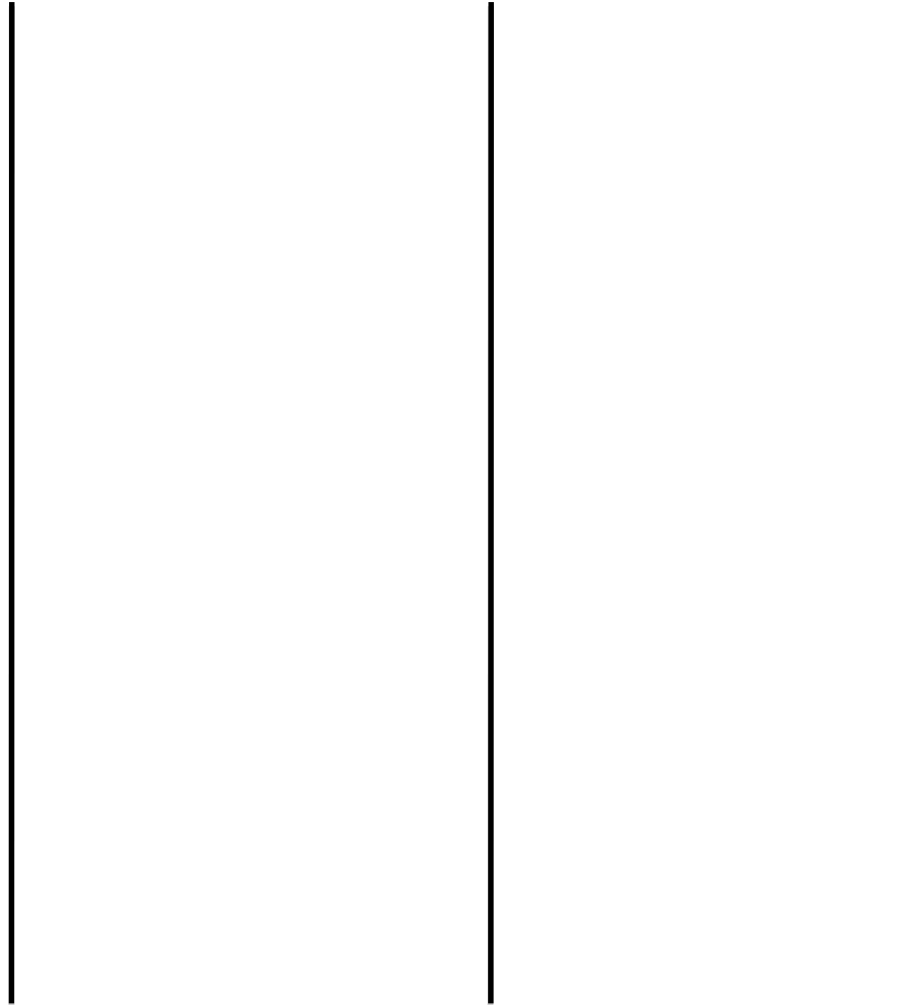
Case 1

X0

X1

TIME  
↓

Success

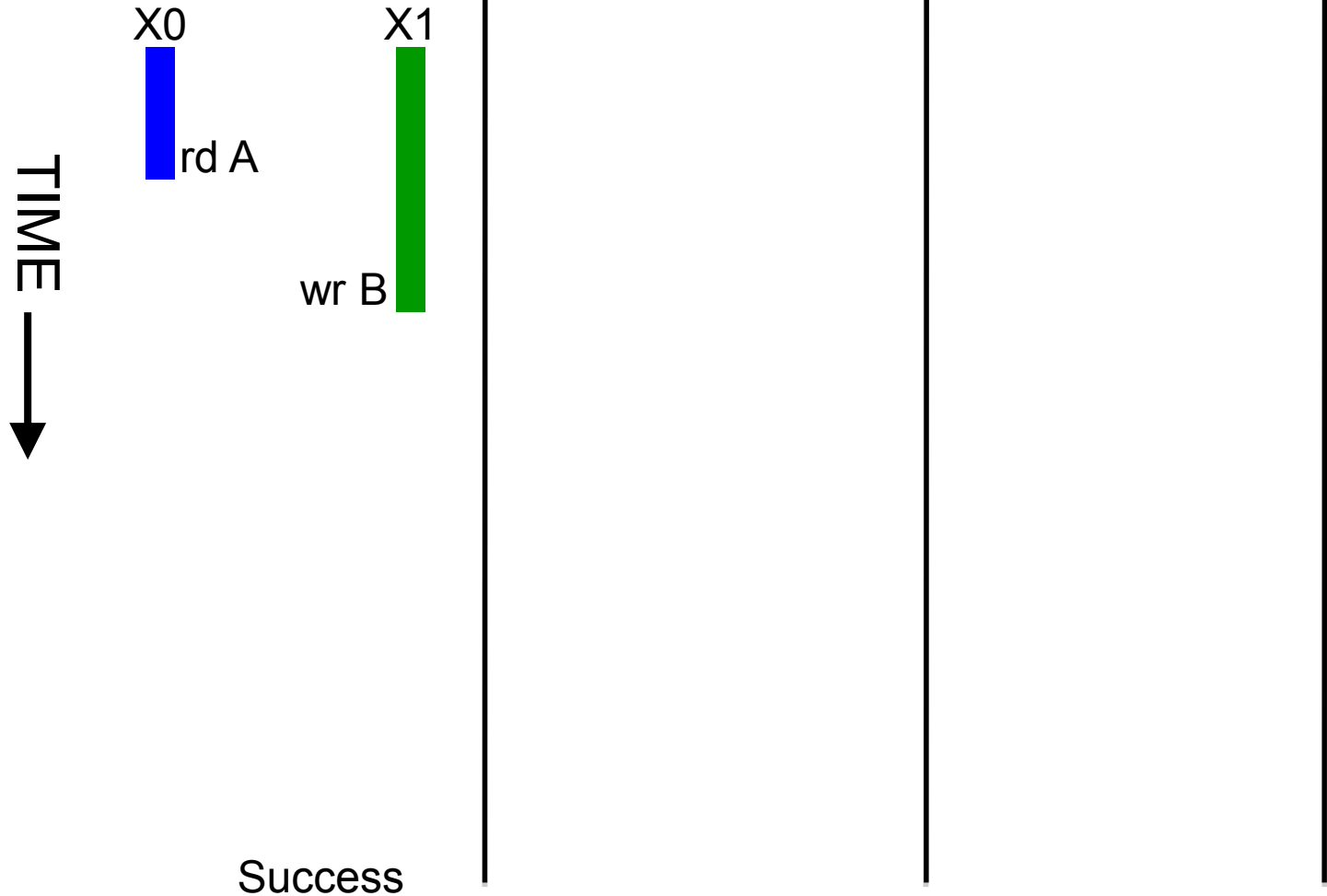




# Optimistic Detection Illustration

---

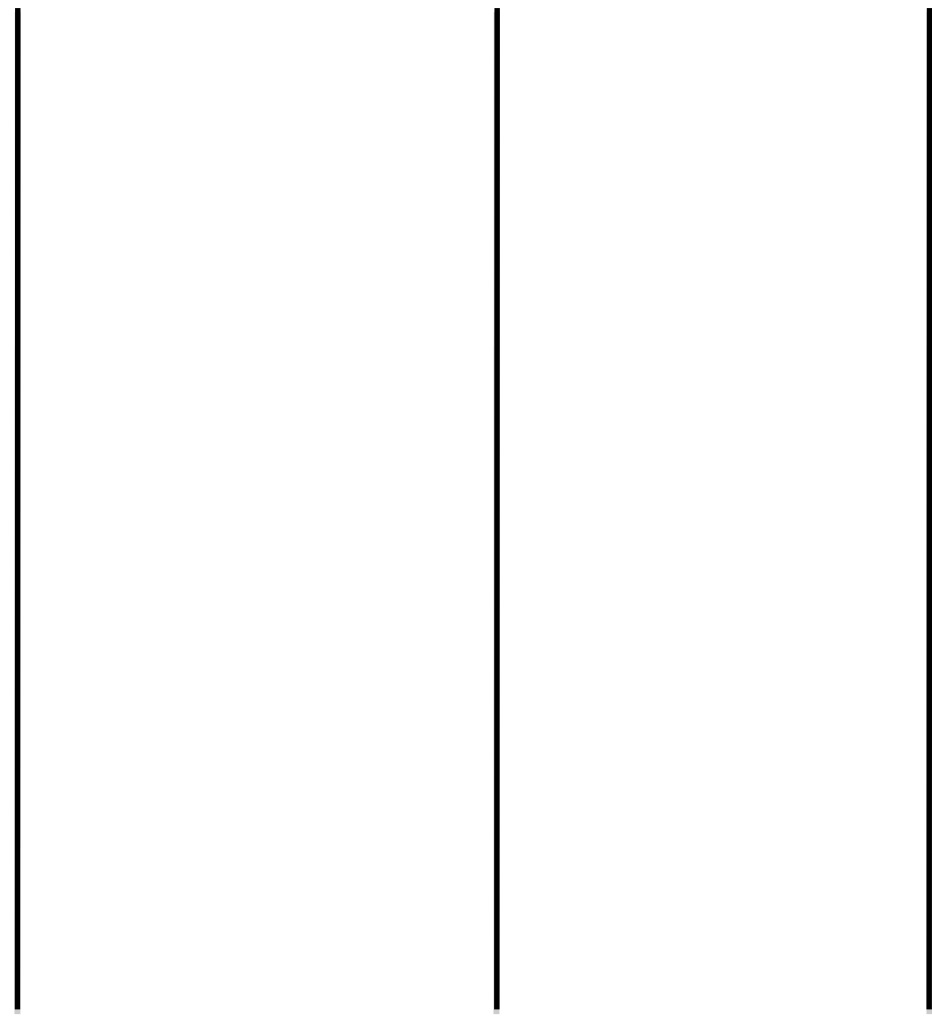
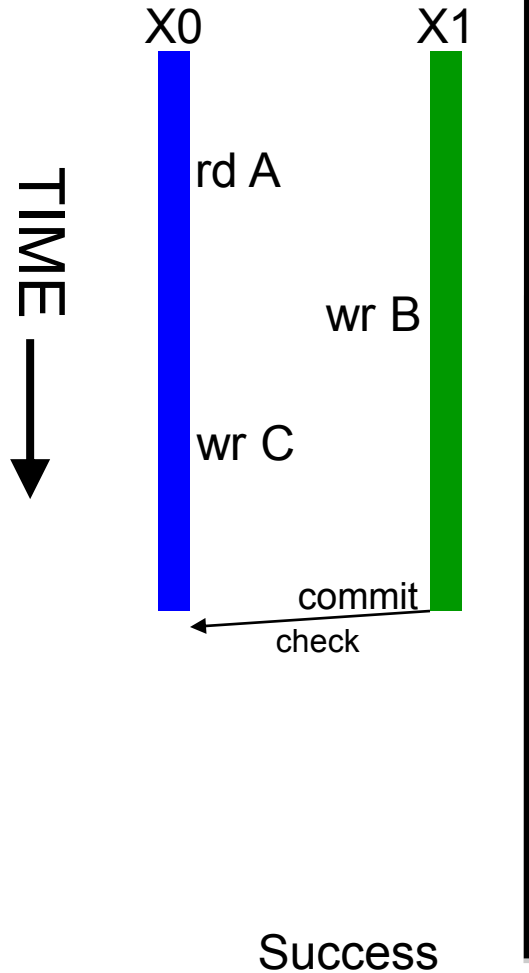
Case 1



# Optimistic Detection Illustration

---

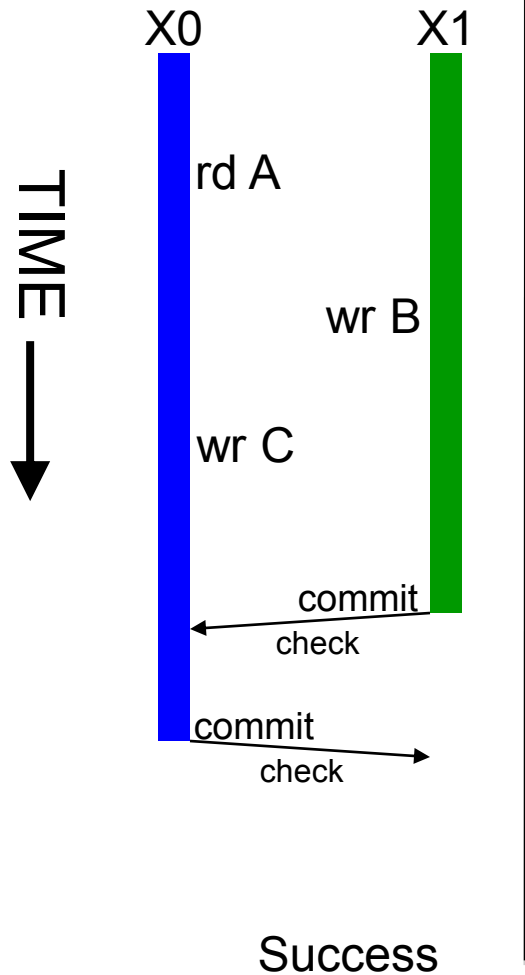
Case 1



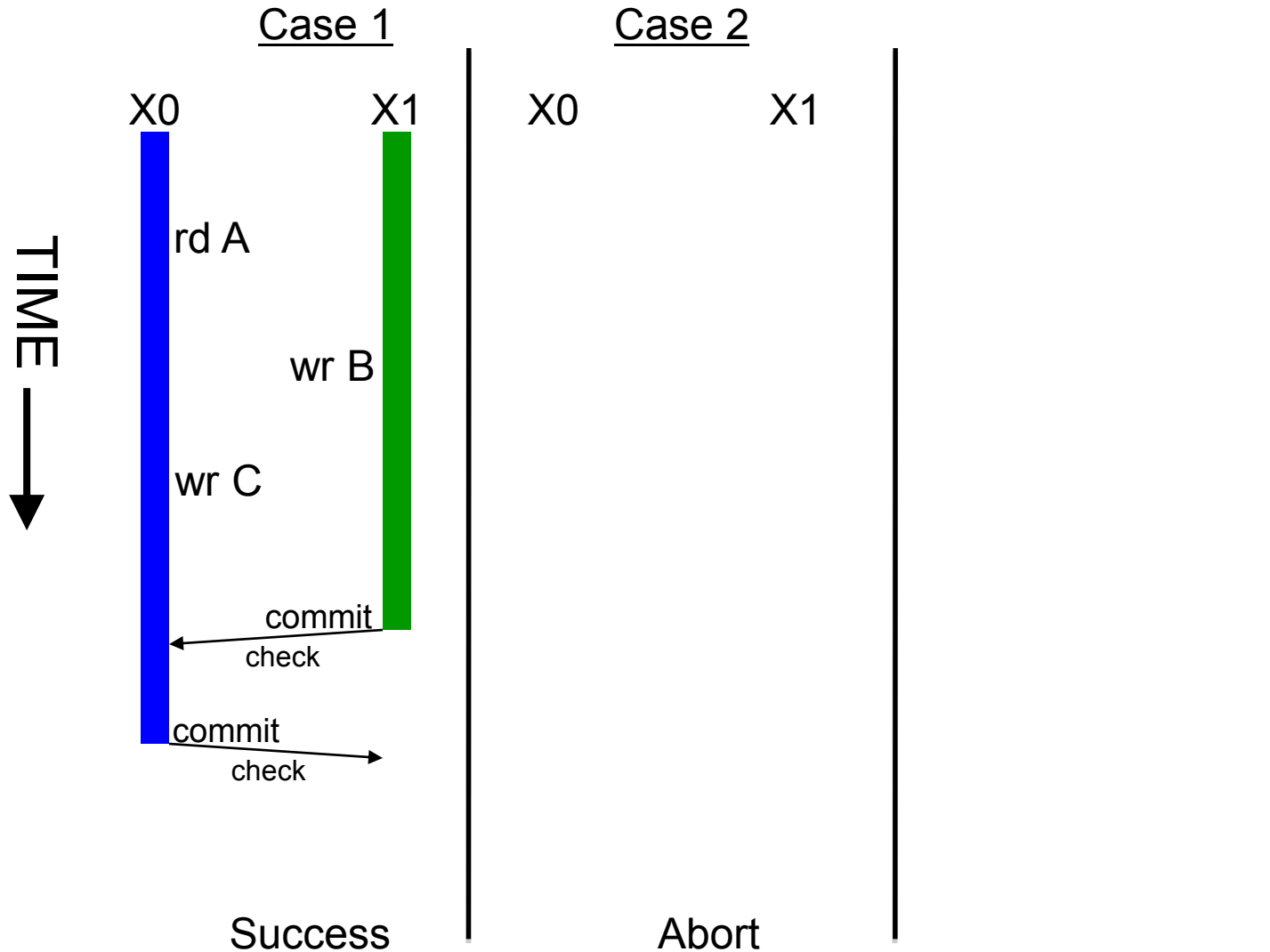
# Optimistic Detection Illustration

---

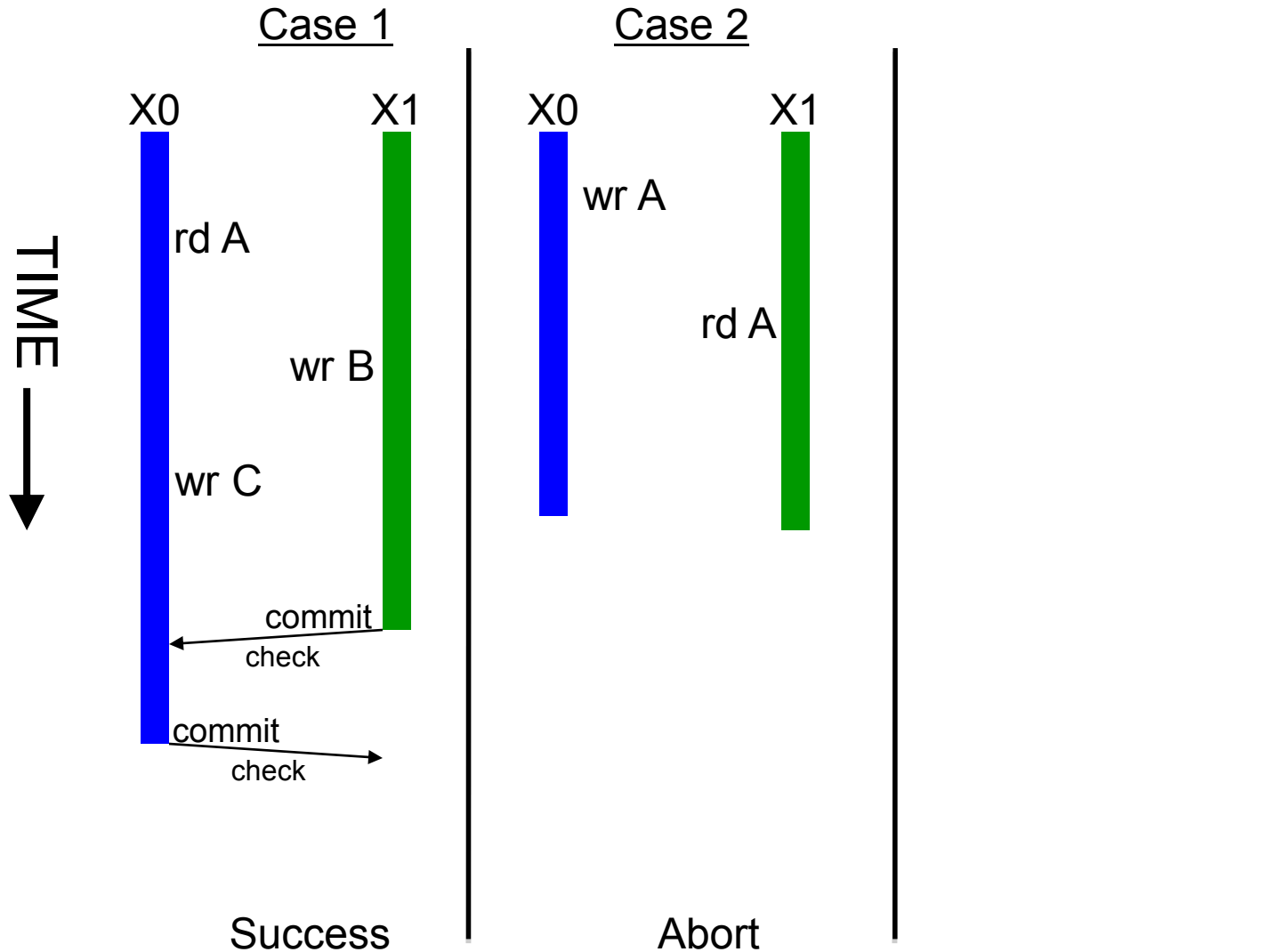
Case 1



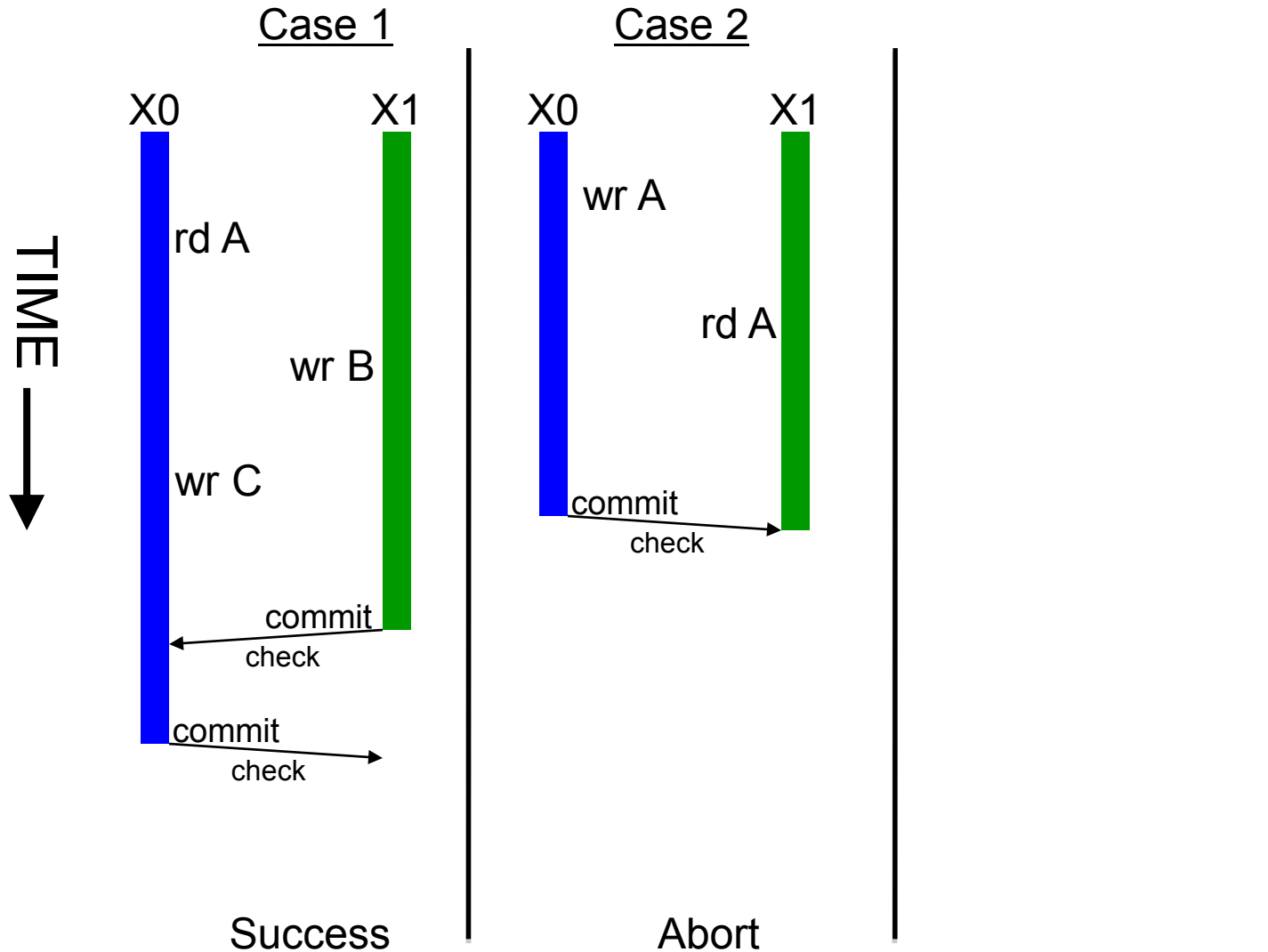
# Optimistic Detection Illustration



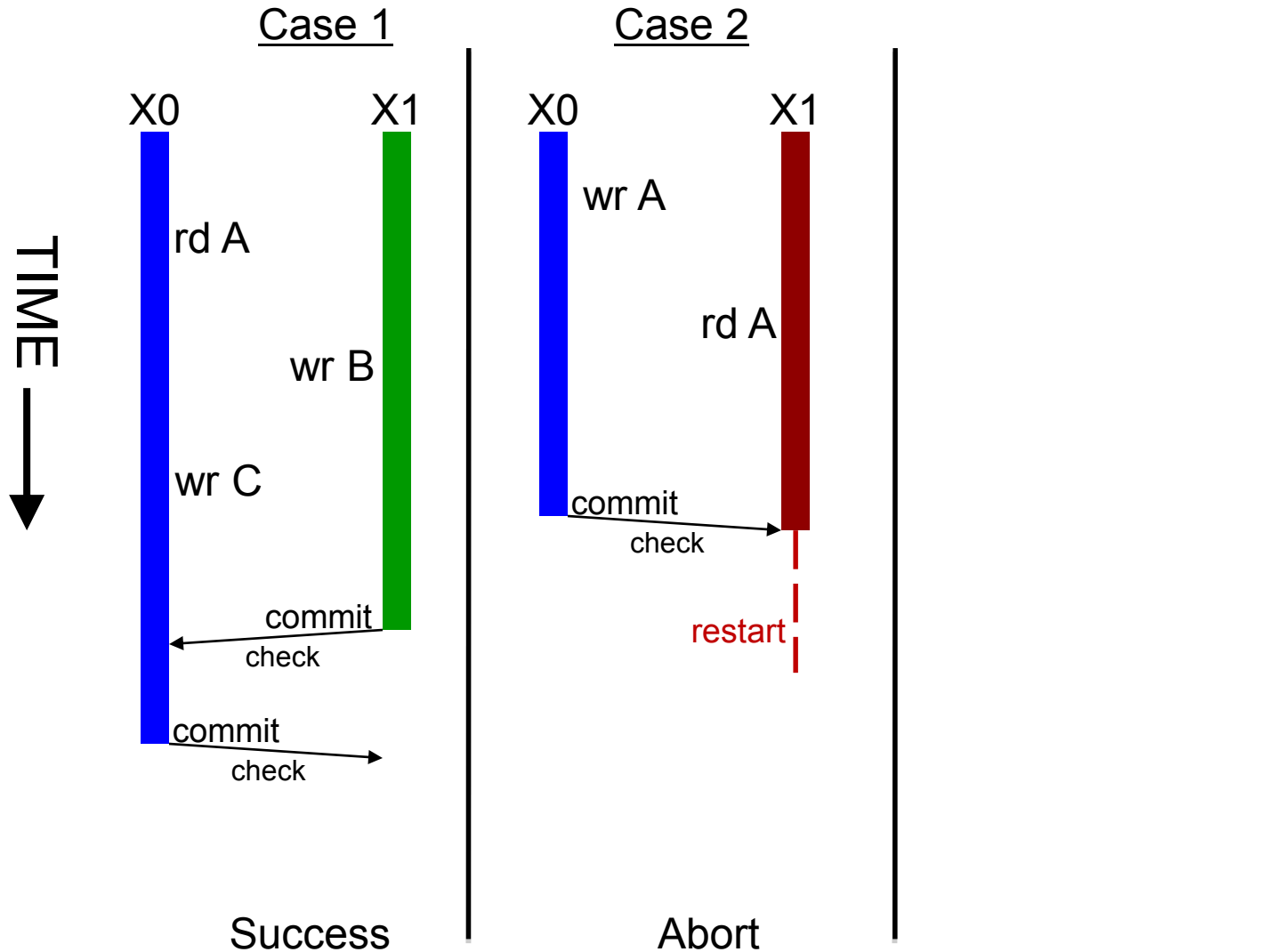
# Optimistic Detection Illustration



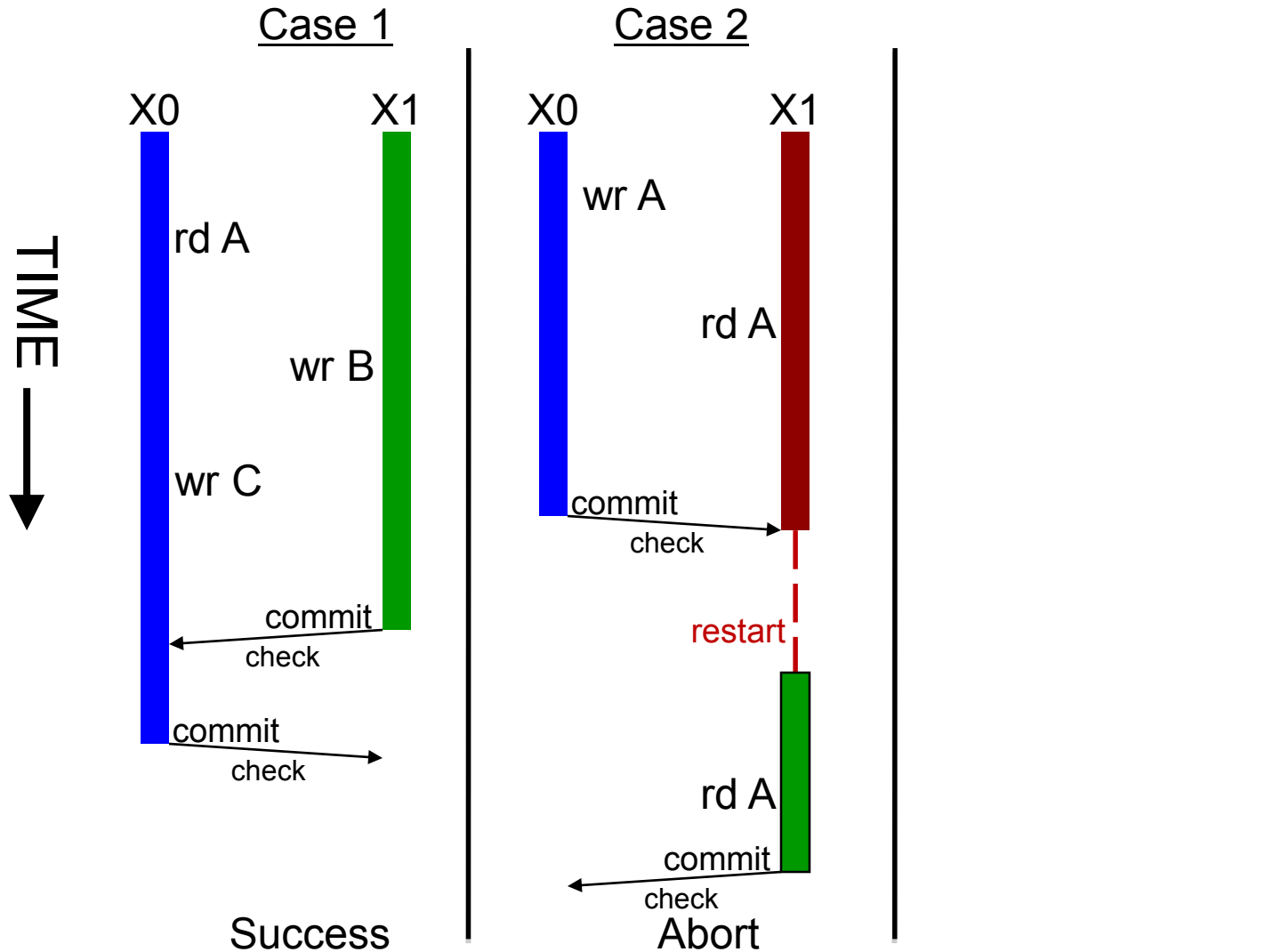
# Optimistic Detection Illustration



# Optimistic Detection Illustration

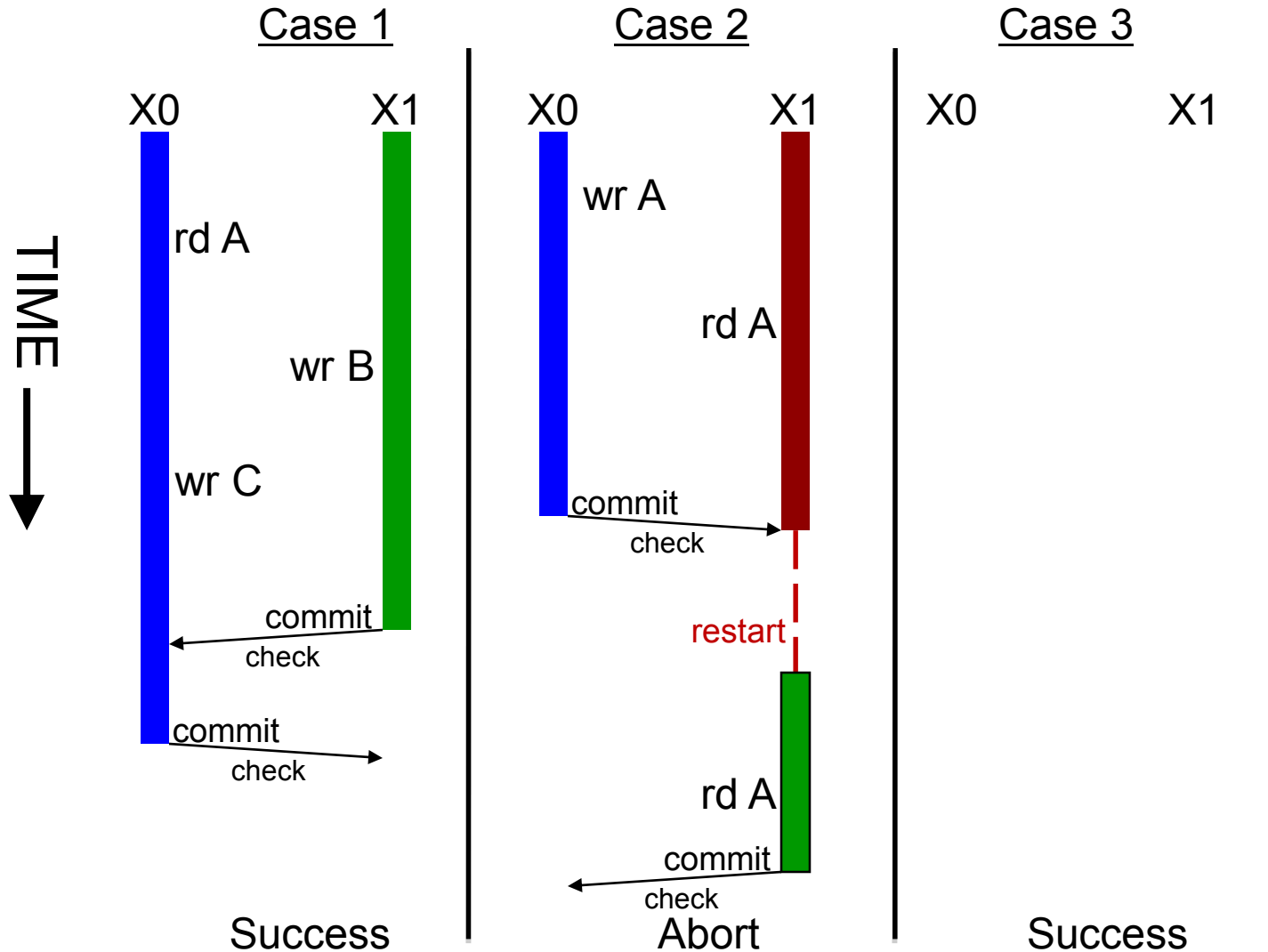


# Optimistic Detection Illustration

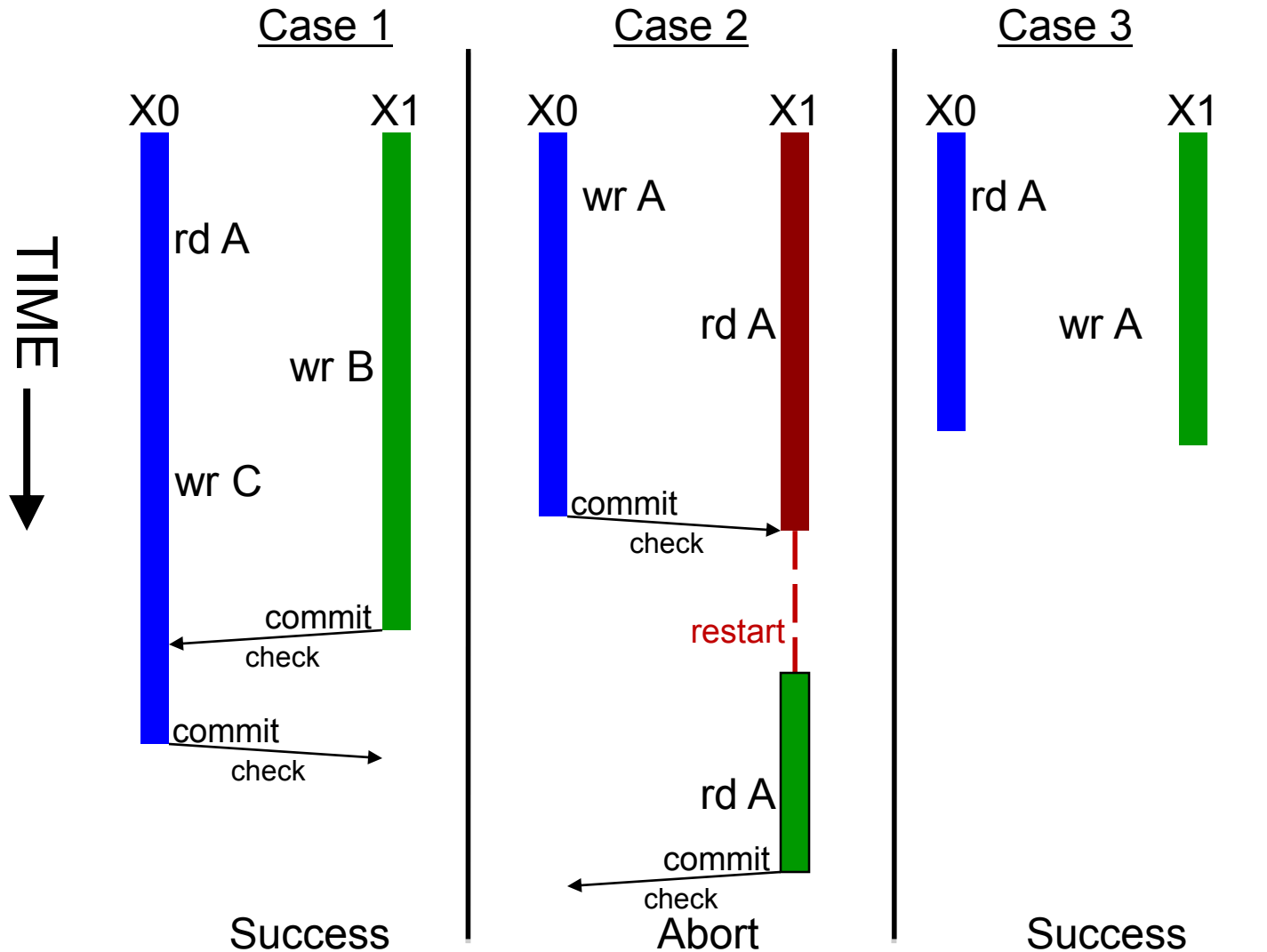




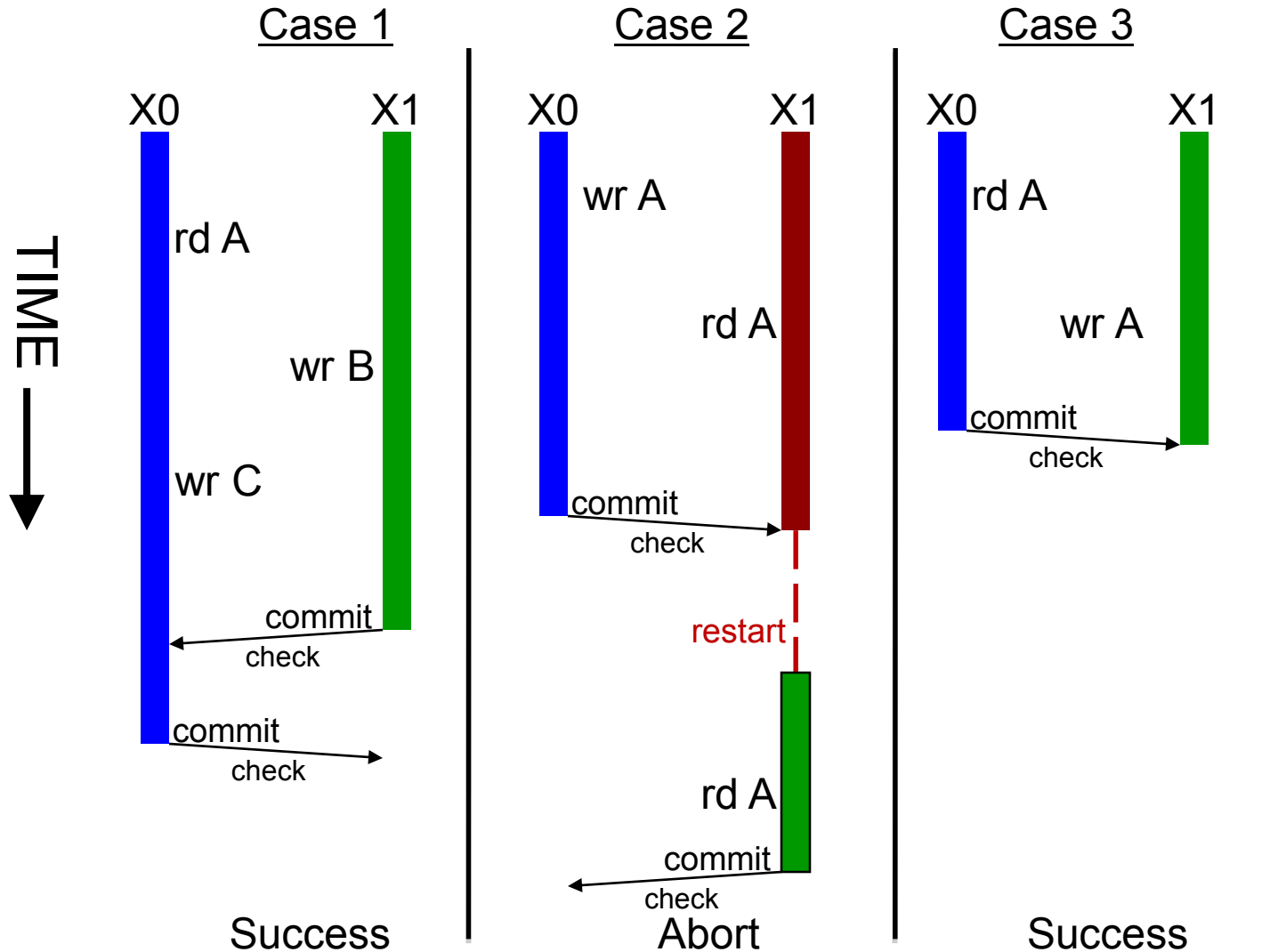
# Optimistic Detection Illustration



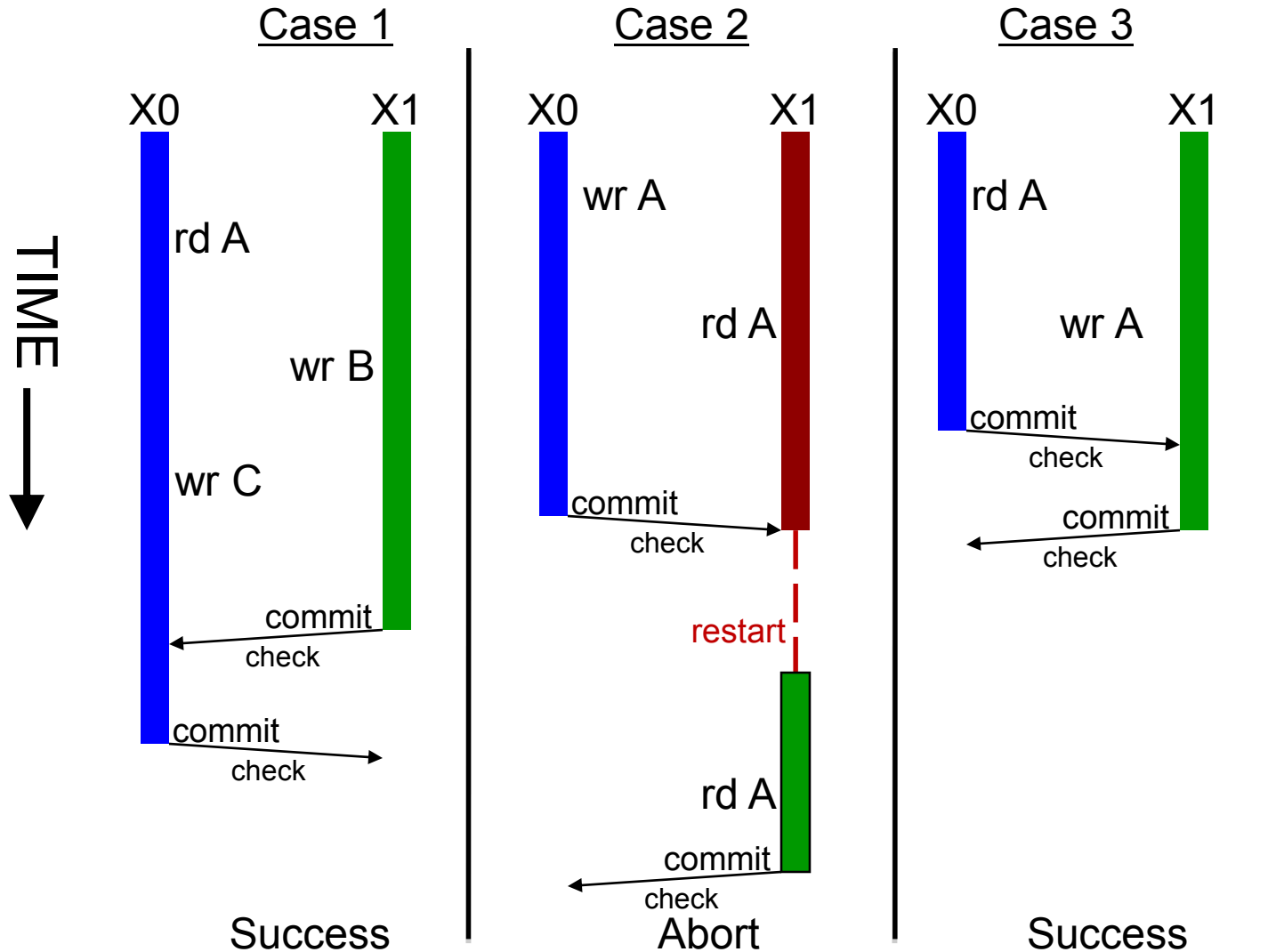
# Optimistic Detection Illustration



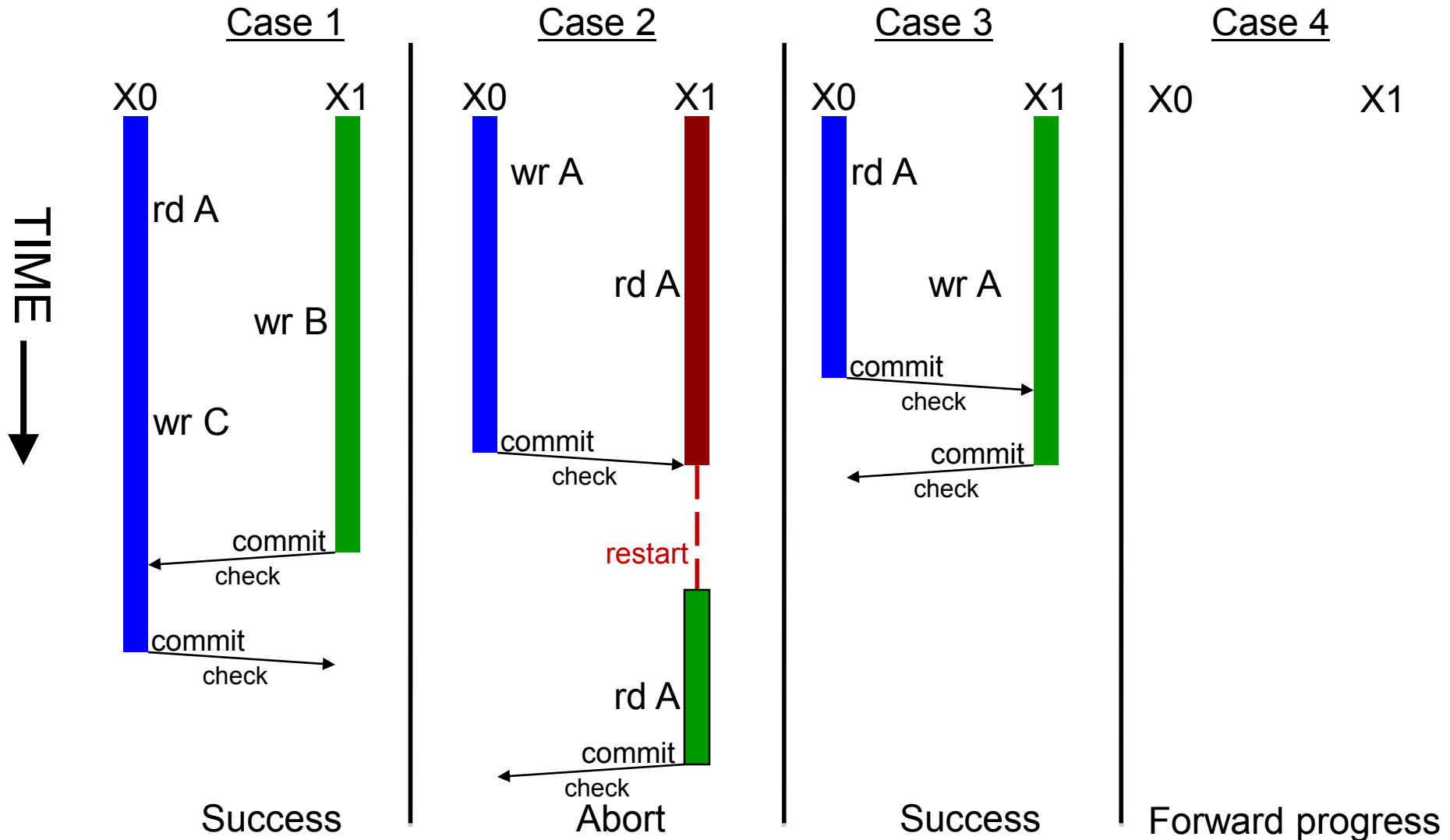
# Optimistic Detection Illustration



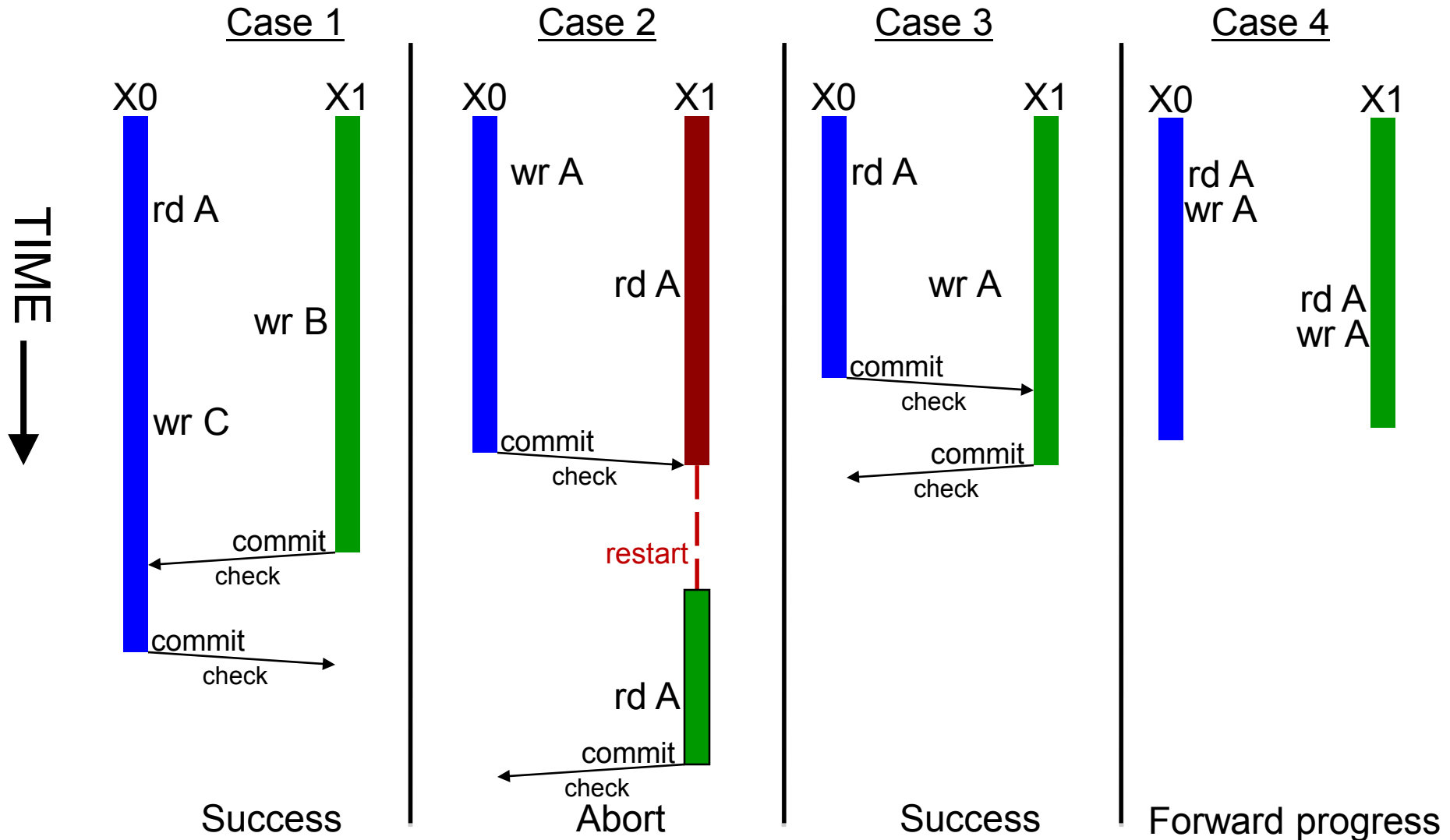
# Optimistic Detection Illustration



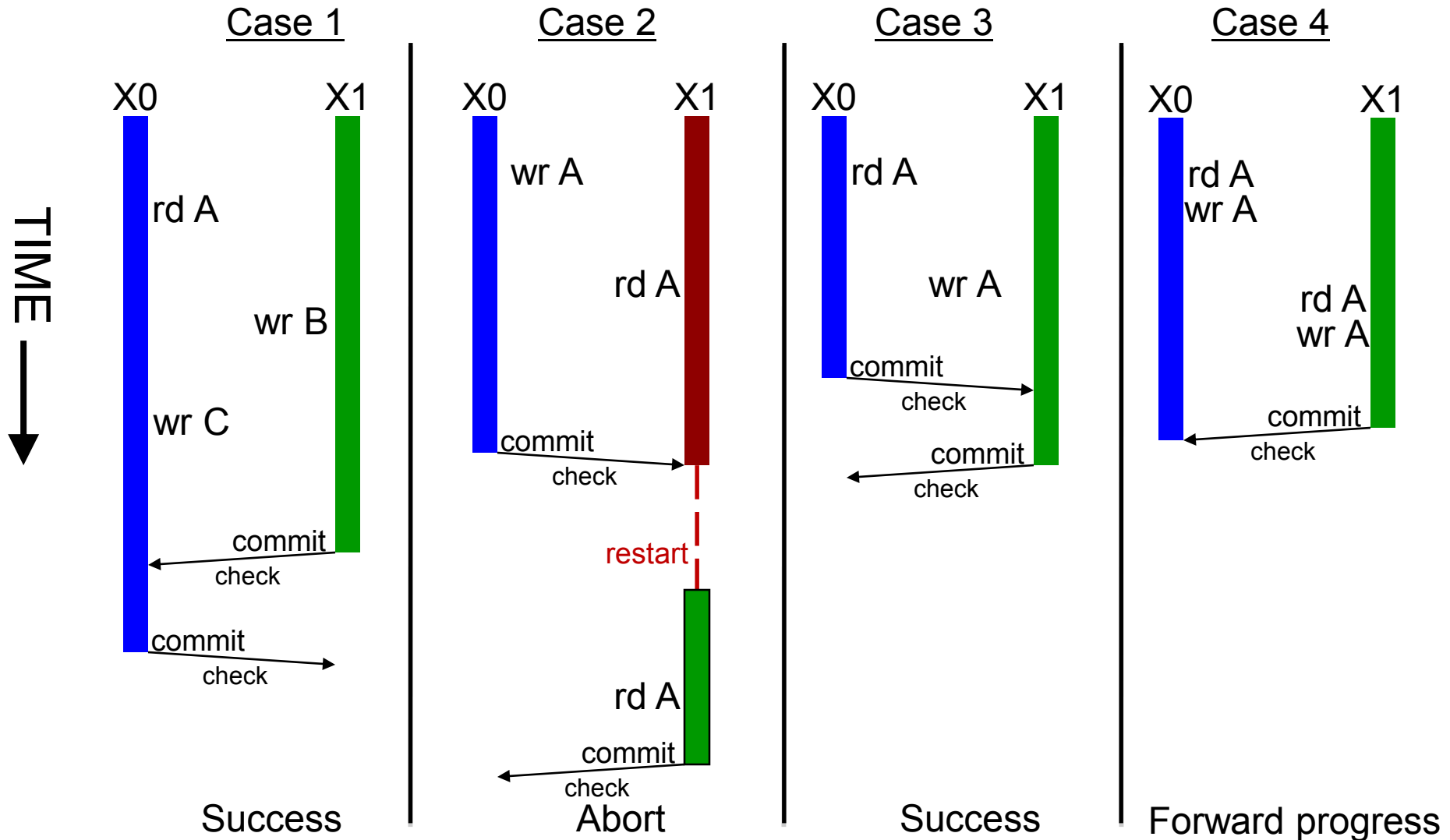
# Optimistic Detection Illustration



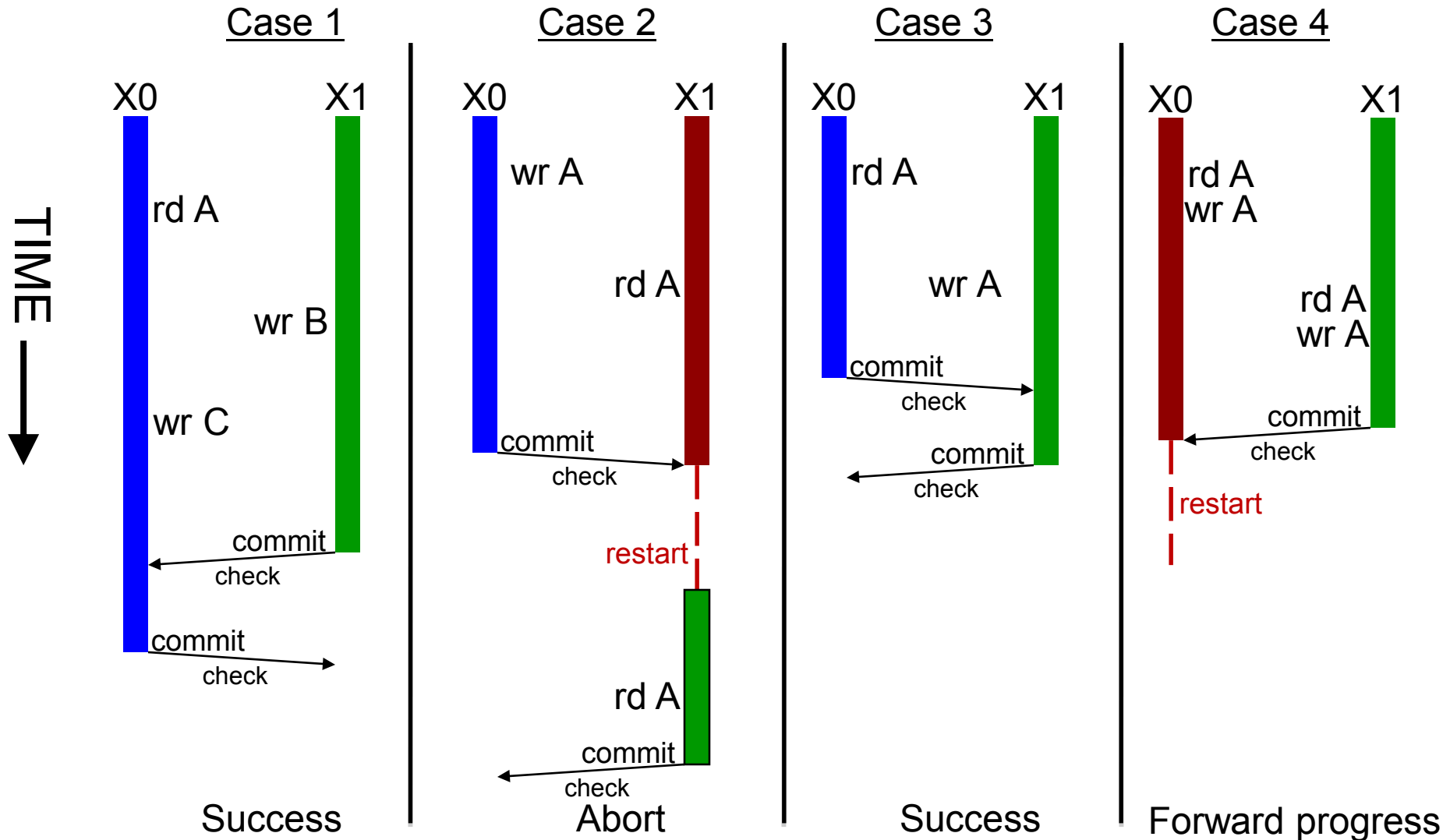
# Optimistic Detection Illustration



# Optimistic Detection Illustration

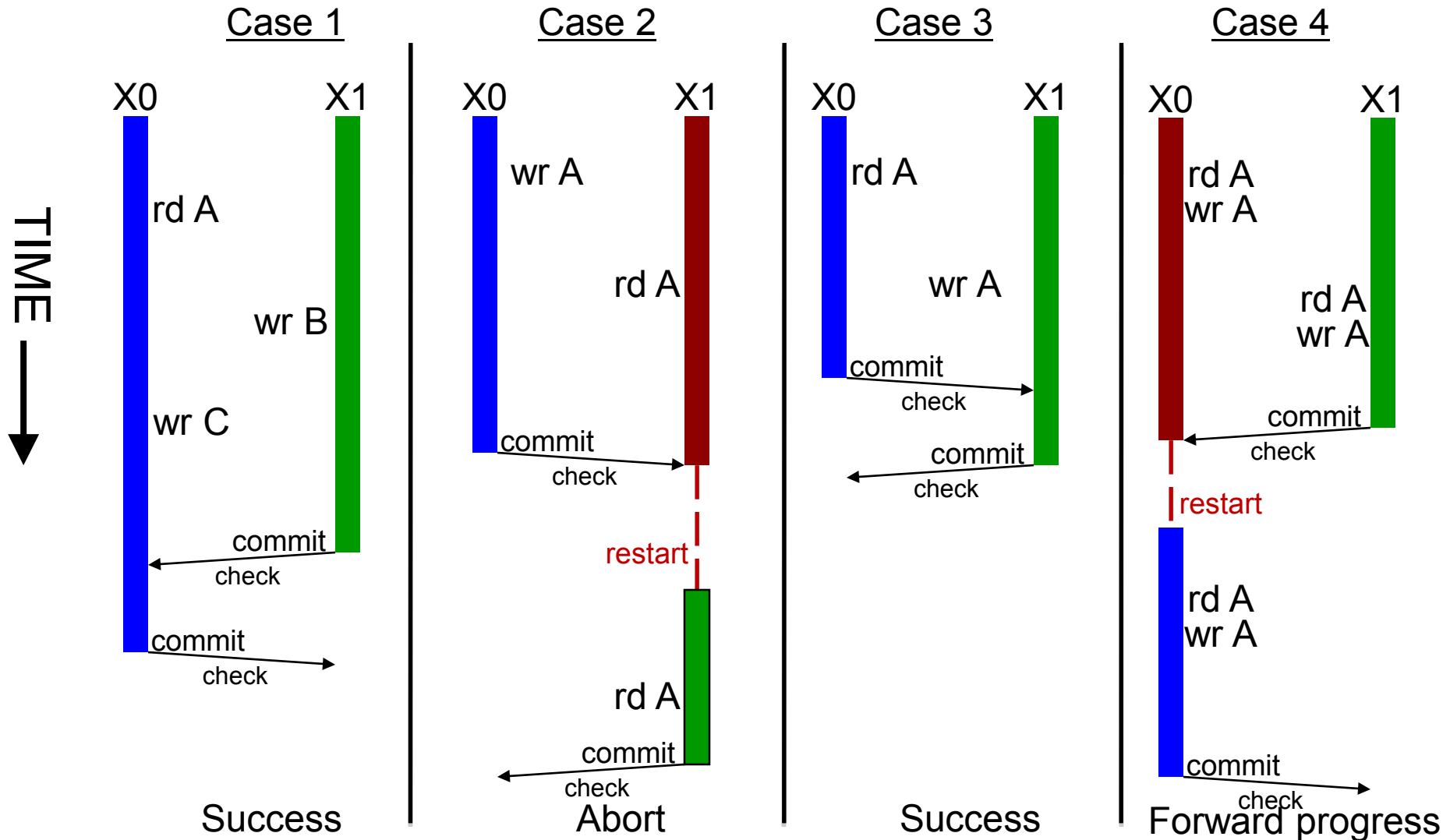


# Optimistic Detection Illustration





# Optimistic Detection Illustration



# Conflict Detection Tradeoffs

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## 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

# 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

# HTM Implementation Overview

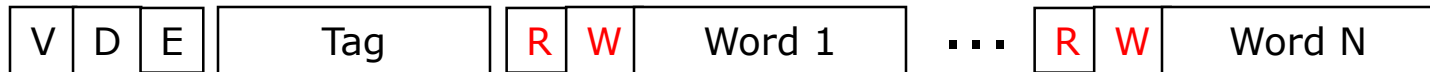
---

- 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

---

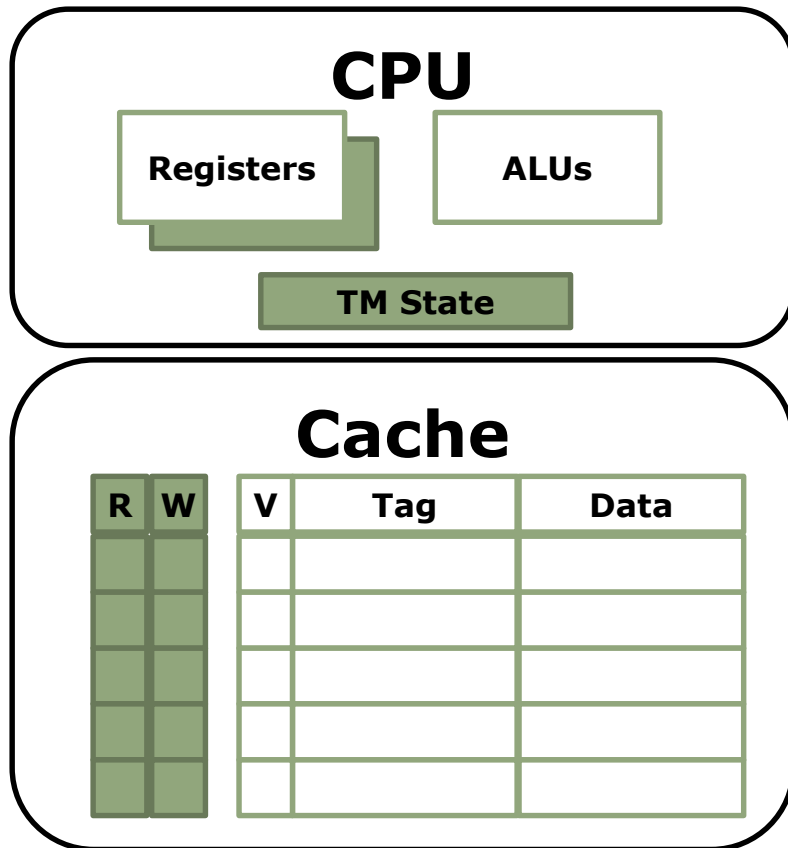
- Cache lines track read-set & write-set
  - R bit: indicates data read by transaction; set on load
  - W bit: indicates data written by transaction; set on store
  - R/W bits can be at word or cache-line granularity
  - R/W bits gang-cleared on transaction commit or abort



- 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

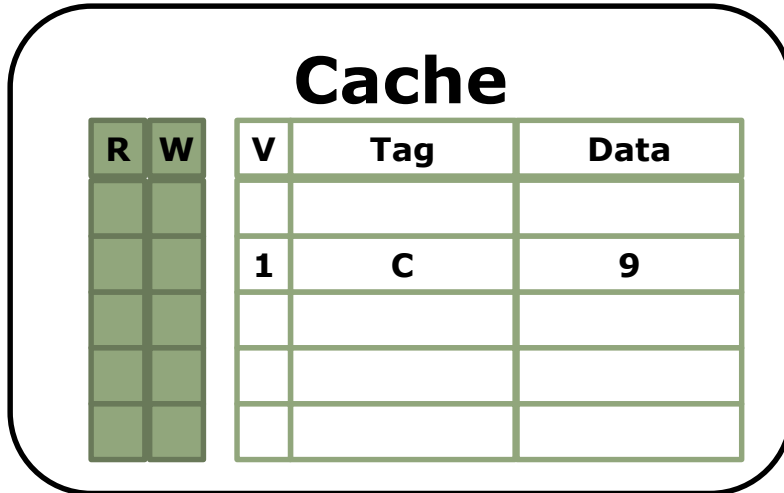
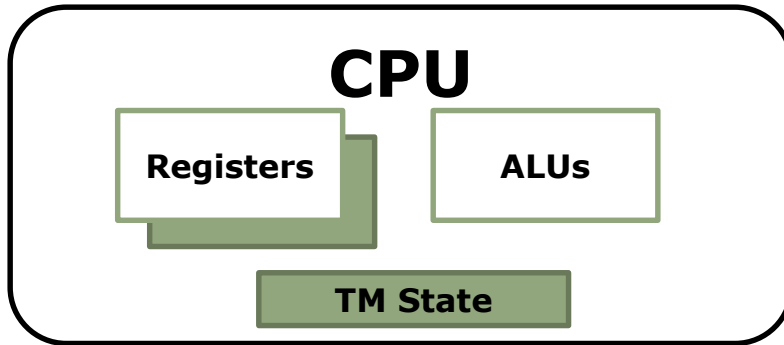
---



- 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

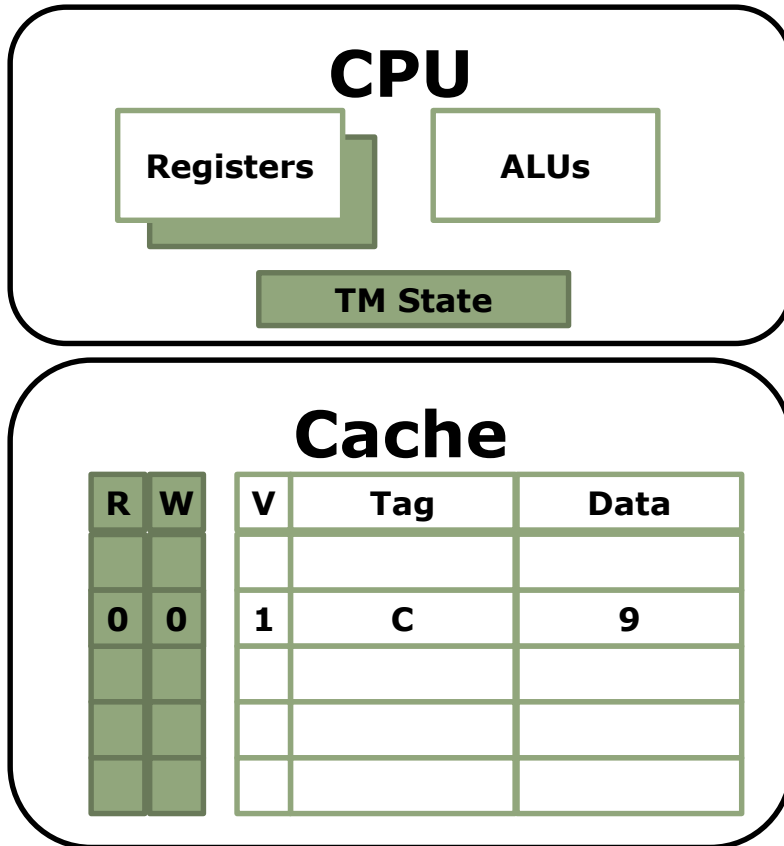
Store B  $\leftarrow$  5

Load C

**Xcommit**



# HTM Transaction Execution



Xbegin ←

Load A

Store B ← 5

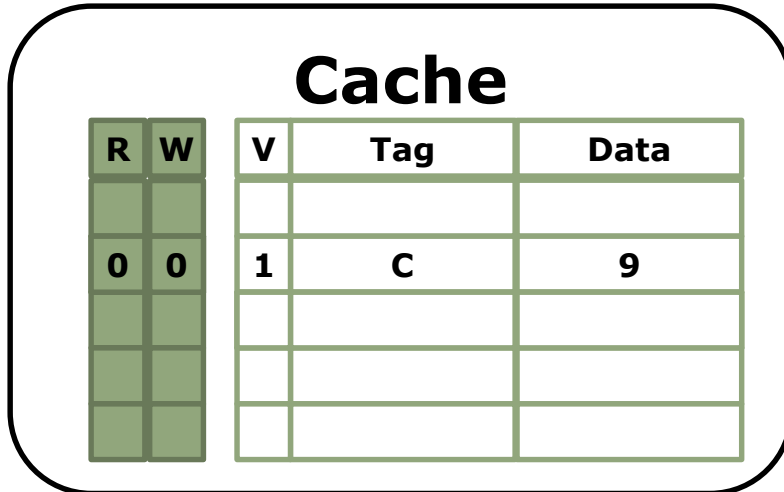
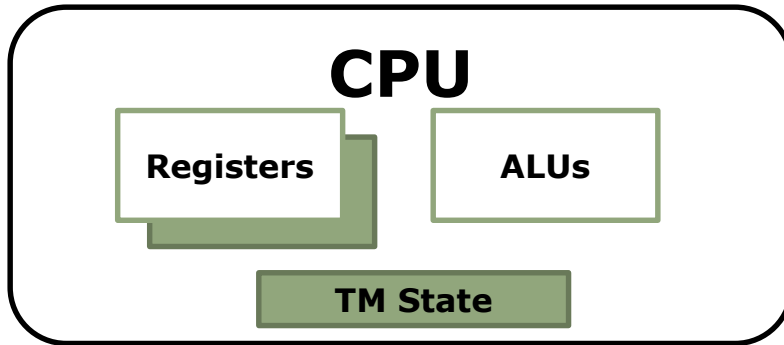
Load C

Xcommit

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

# HTM Transaction Execution

---



**Xbegin**

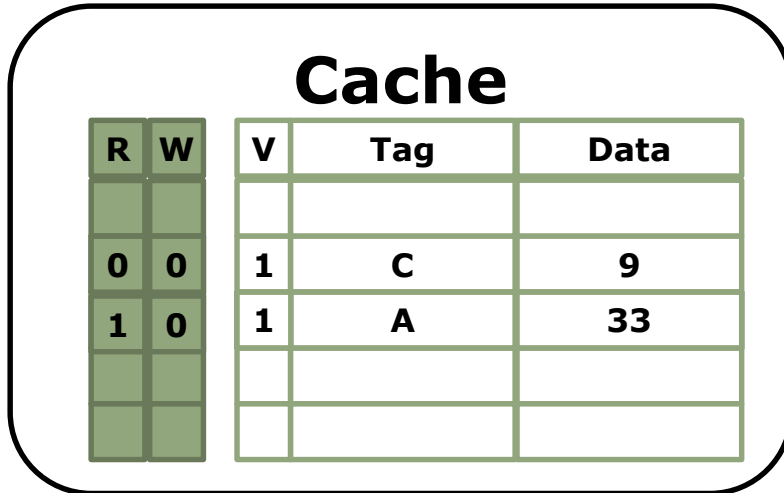
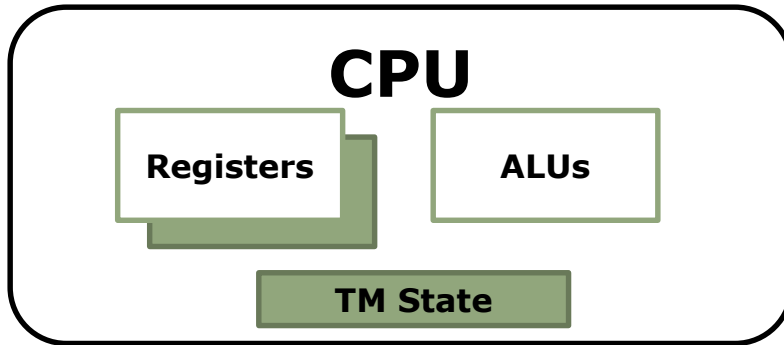
Load A ←

Store B ← 5

Load C

**Xcommit**

# HTM Transaction Execution



**Xbegin**

Load A ←

Store B ← 5

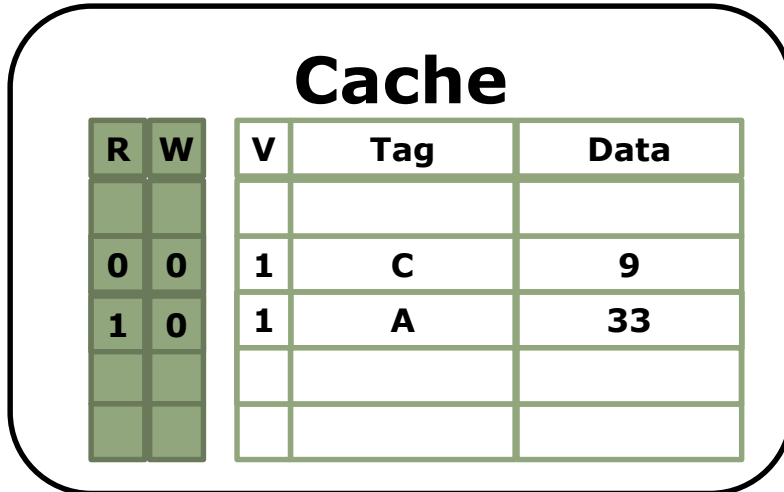
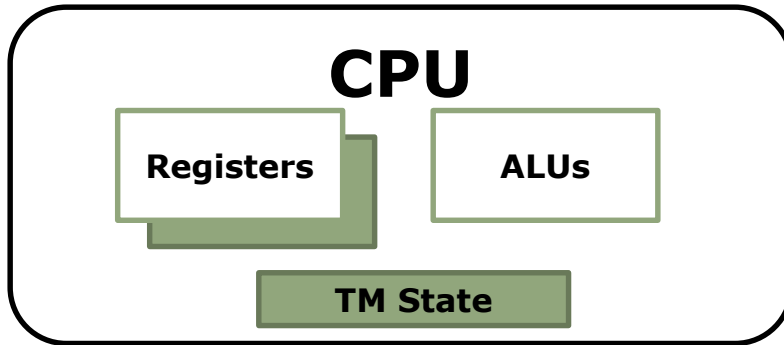
Load C

**Xcommit**

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

# HTM Transaction Execution

---



Xbegin

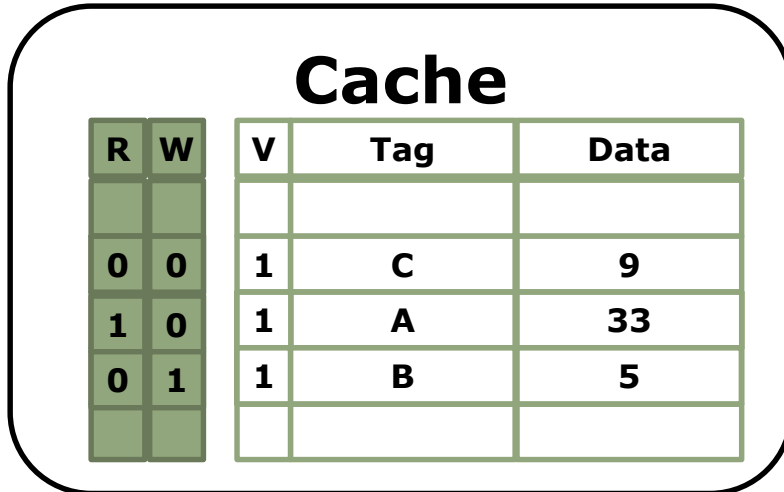
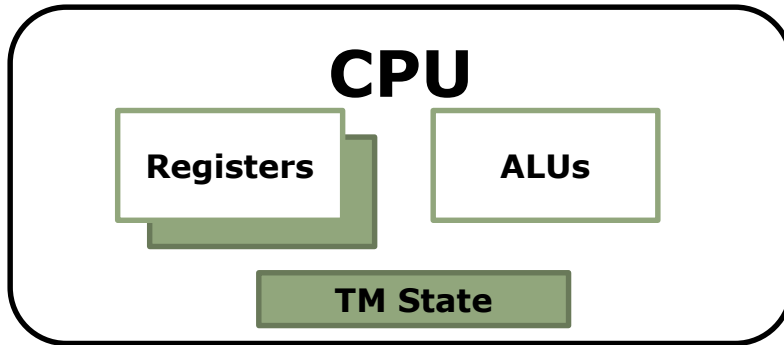
Load A

Store B  $\leftarrow$  5  $\leftarrow$

Load C

Xcommit

# HTM Transaction Execution



**Xbegin**

Load A

Store B  $\leftarrow$  5  $\leftarrow$

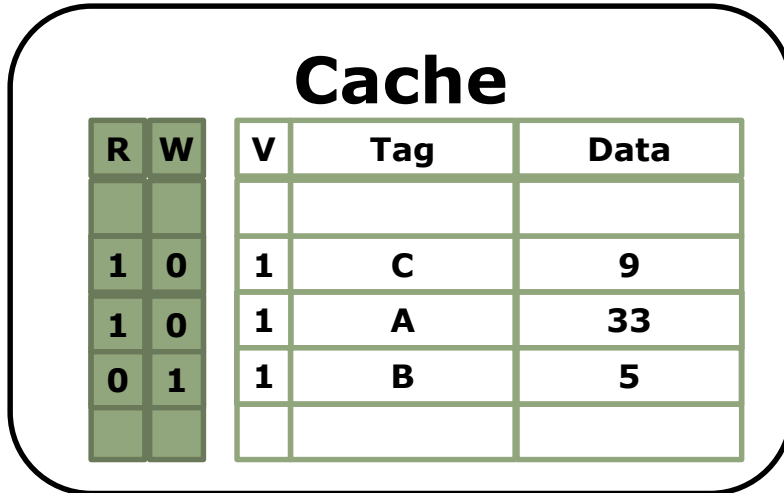
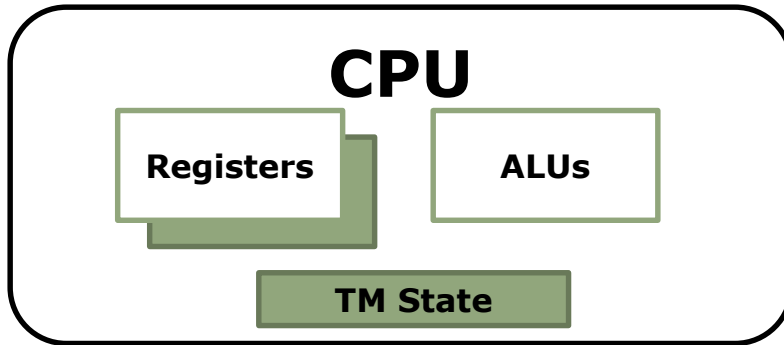
Load C

**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

---



Xbegin

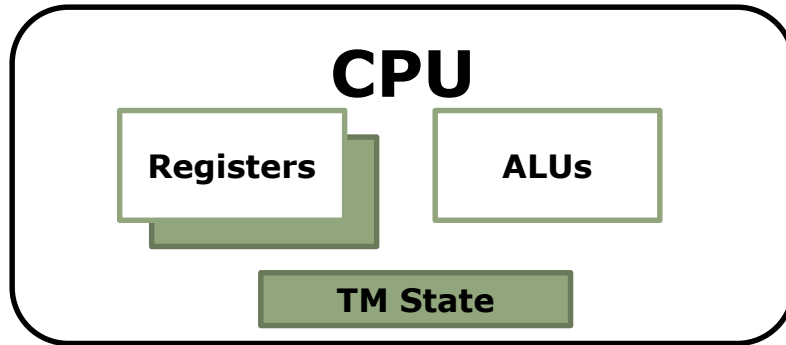
Load A

Store B  $\leftarrow$  5

Load C

Xcommit  $\leftarrow$

# HTM Transaction Execution



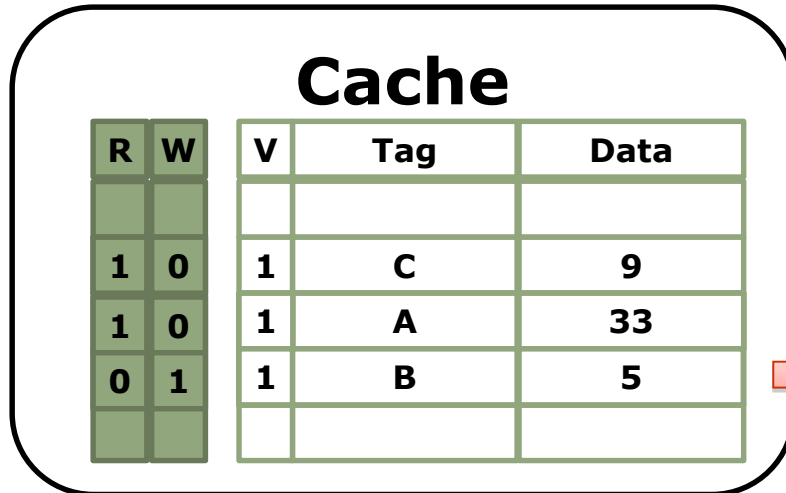
Xbegin

Load A

Store B  $\leftarrow$  5

Load C

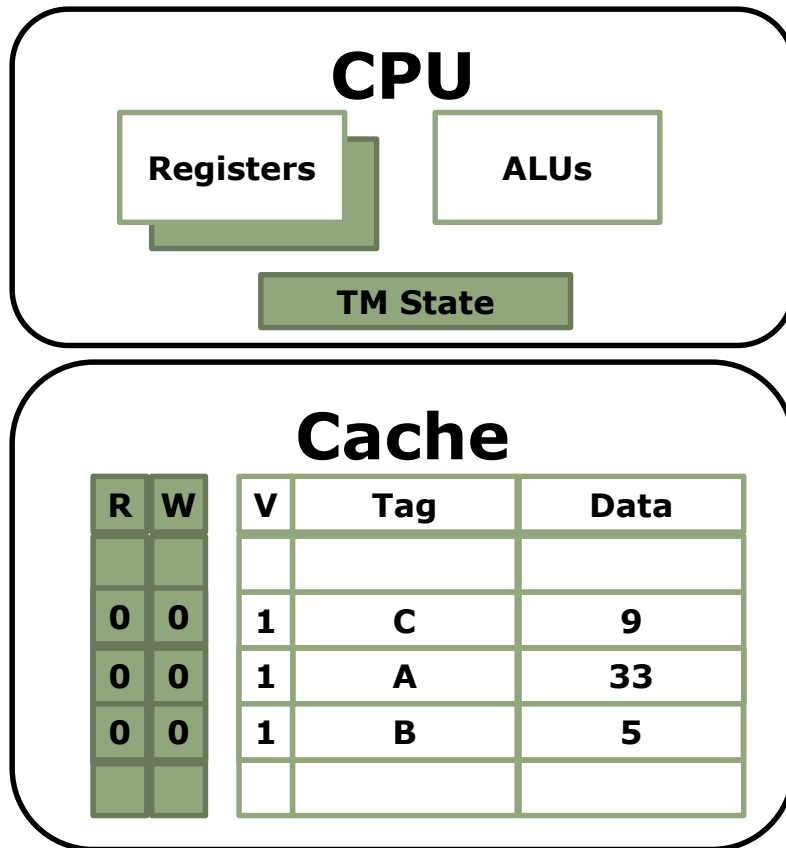
Xcommit  $\leftarrow$



 upgradeX B

- Fast 2-phase commit:
  - Validate: Request exclusive access to write-set lines (if needed)

# HTM Transaction Execution



Xbegin

Load A

Store B  $\leftarrow$  5

Load C

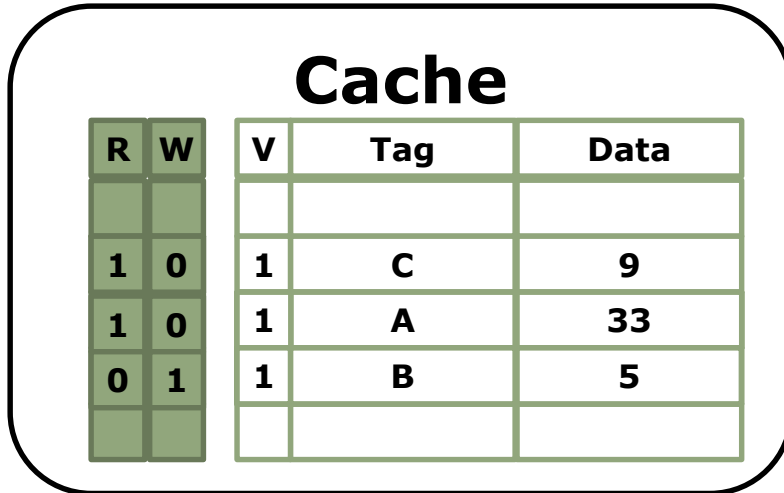
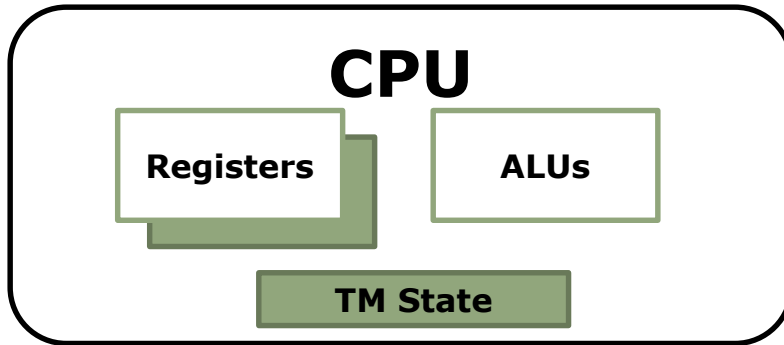
Xcommit  $\leftarrow$

- 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

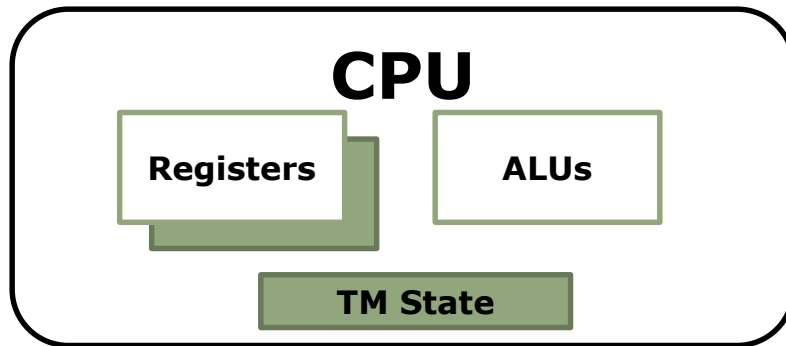
Store B  $\leftarrow$  5

Load C  $\leftarrow$

**Xcommit**

- Fast conflict detection & abort:

# HTM Conflict Detection



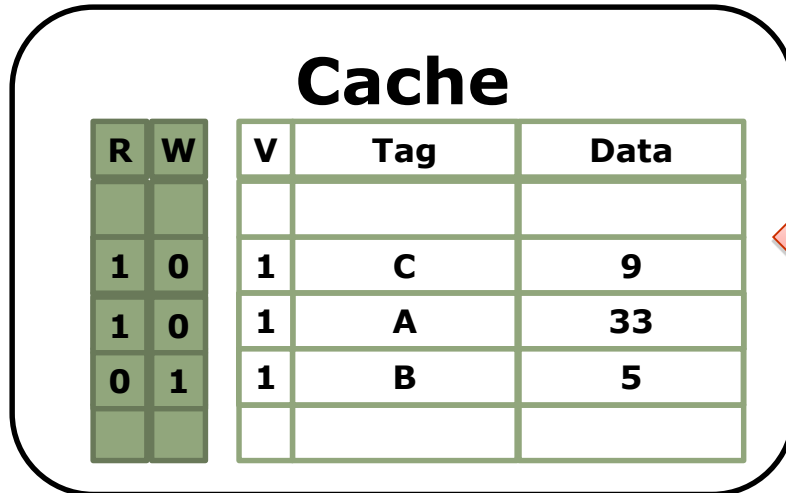
**Xbegin**

Load A

Store B  $\leftarrow$  5

Load C  $\leftarrow$

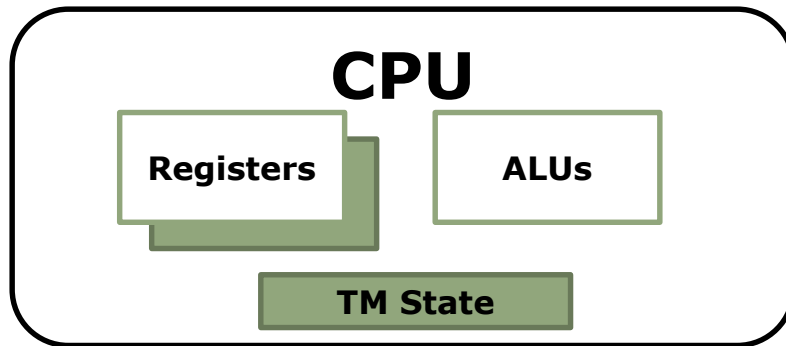
**Xcommit**



 upgradeX D

- Fast conflict detection & abort:
  - Check: Lookup exclusive requests in the read-set and write-set

# HTM Conflict Detection



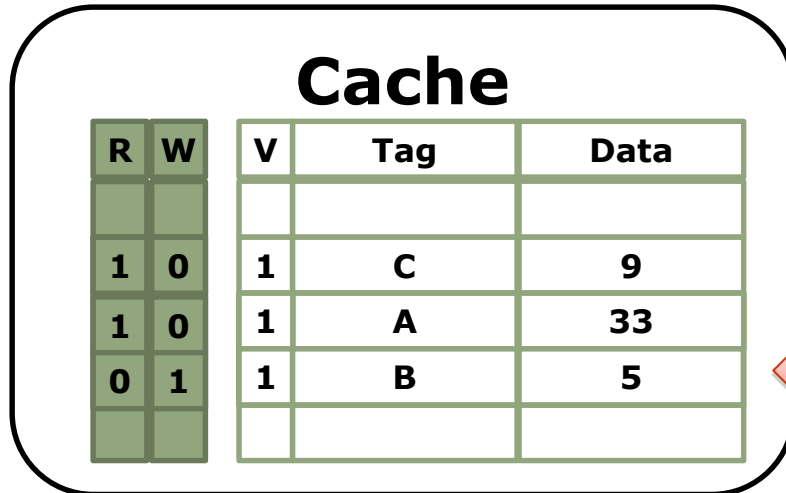
**Xbegin**

Load A

Store B  $\leftarrow$  5

Load C  $\leftarrow$

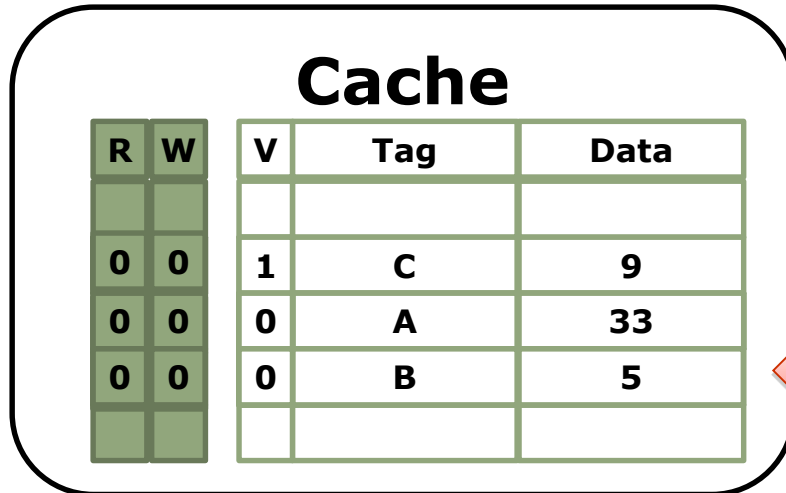
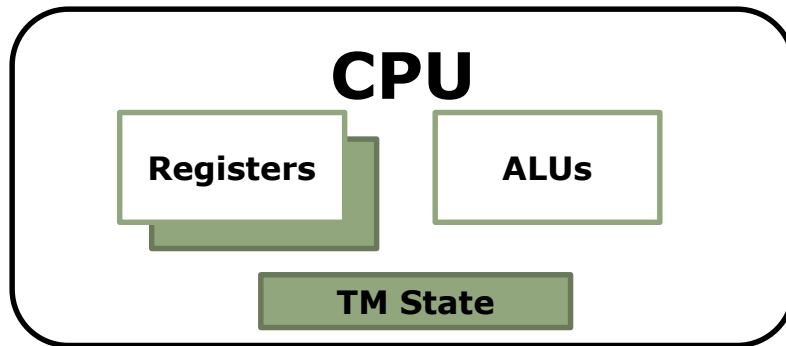
**Xcommit**



$\leftarrow$  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 Conflict Detection



**Xbegin**

Load A

Store B  $\leftarrow$  5

Load C  $\leftarrow$

**Xcommit**

$\leftarrow$  upgradeX A  $\boxed{\times}$

- 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

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

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  - 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...



# 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