Concurrency and Synchronization

CS 202: Advanced Operating Systems

UCR
UNIVERSITY OF CALIFORNIA, RIVERSIDE

(some slides credit to Christo Wilson)

Classic Example

- Consider a bank application with a withdrawal function:

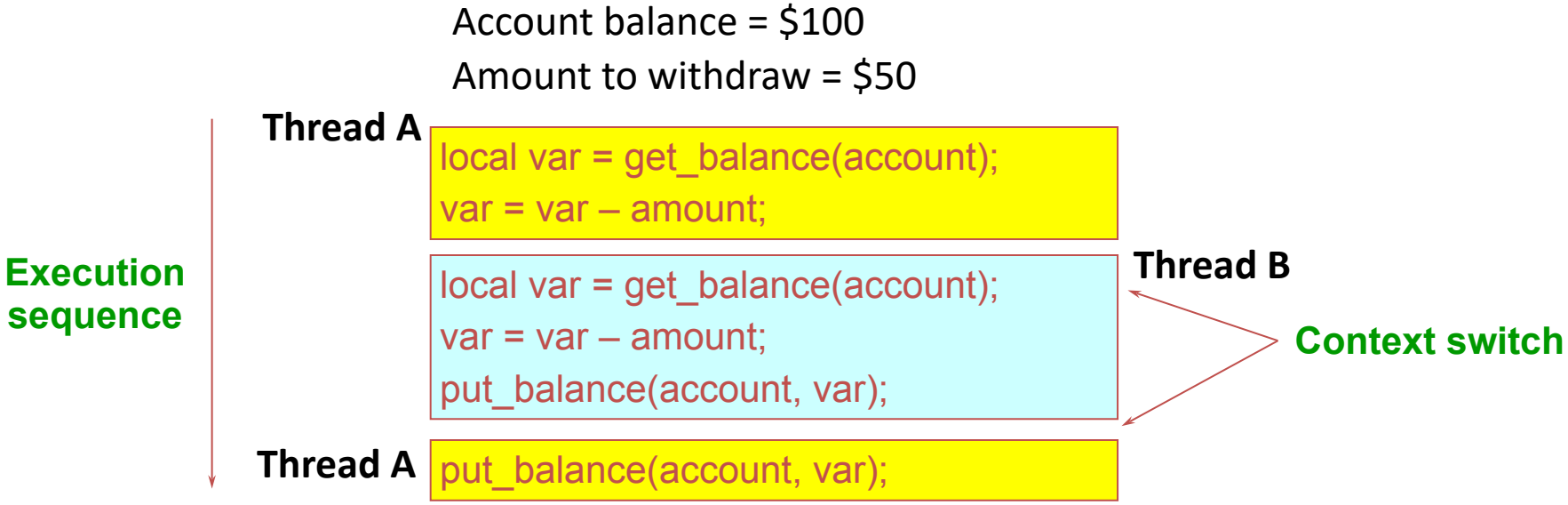
```
withdraw (account, amount) {
    local var = get_balance(account);
    var = var – amount;
    put_balance(account, var);
    return var;
}
```

  - Multi-threaded; each customer request is handled in a separate thread

- What happen if two people try to withdraw money from the same shared account at the same time?

Interleaved Schedules

- The problem is that the execution of the two threads can be interleaved:



- What is the balance of the account now?

Race Conditions

- The previous example shows a race condition
  - Two threads "race" to execute code and update shared (dependent) data
  - Errors emerge based on the ordering of operations, and the scheduling of threads
  - Thus, errors are nondeterministic

Example: Linked List

```
elem pop(&list):
    tmp = list
    list = list->next
    tmp->next = NULL
    return tmp
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```
push(&list, elem):
    elem->next = list
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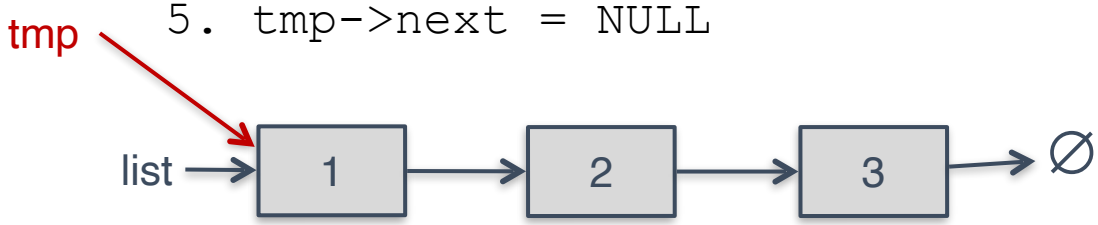

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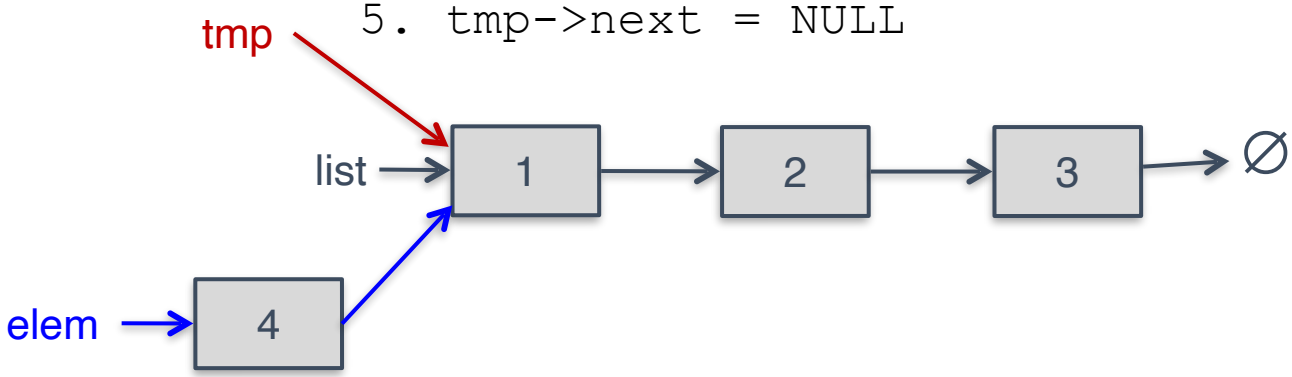

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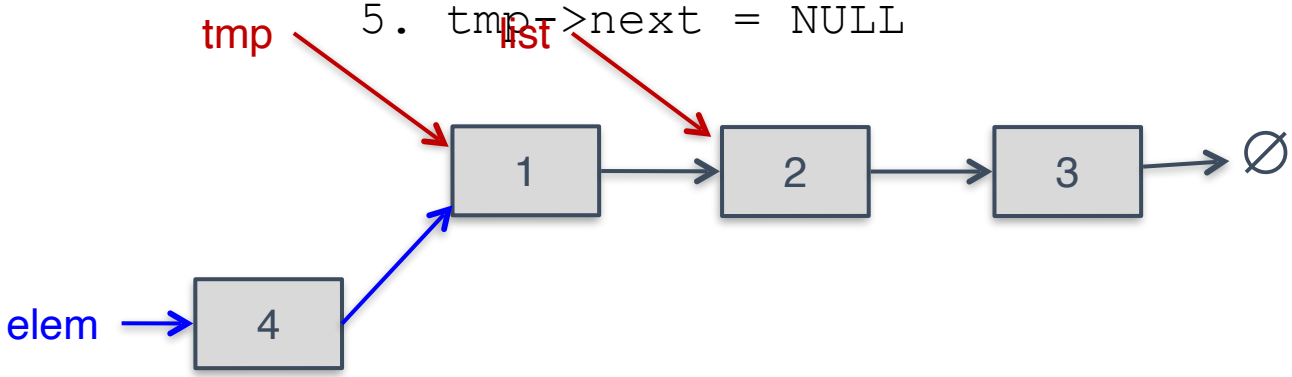

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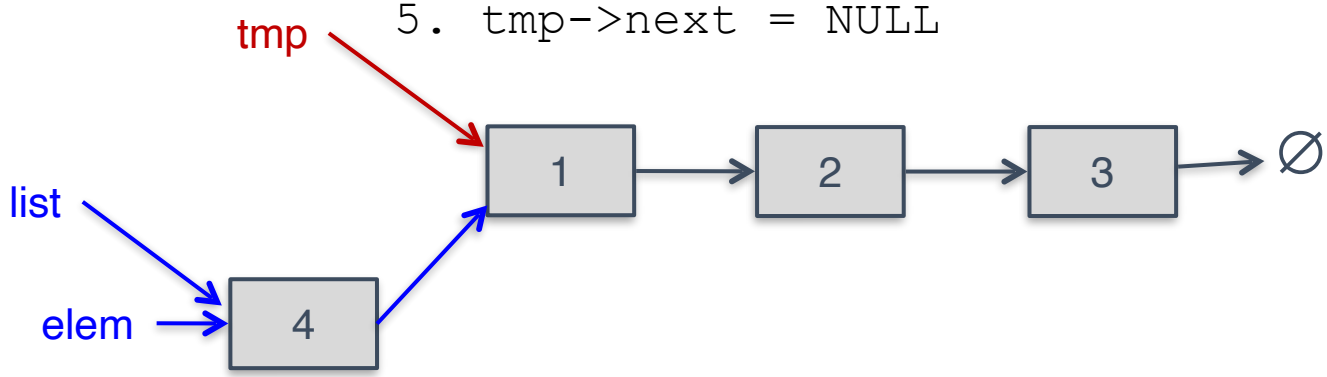

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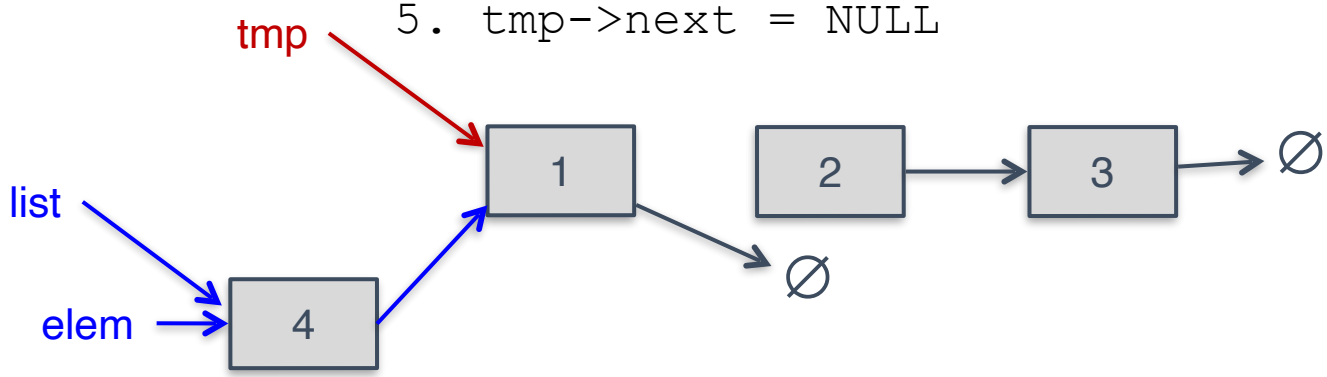

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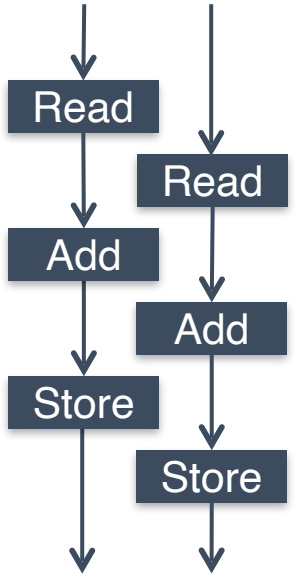

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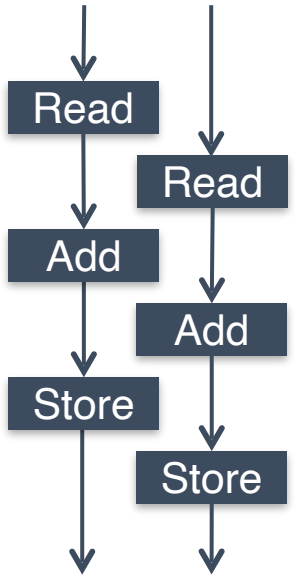

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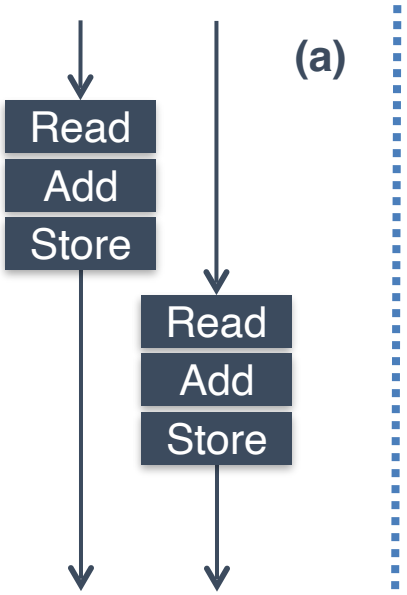

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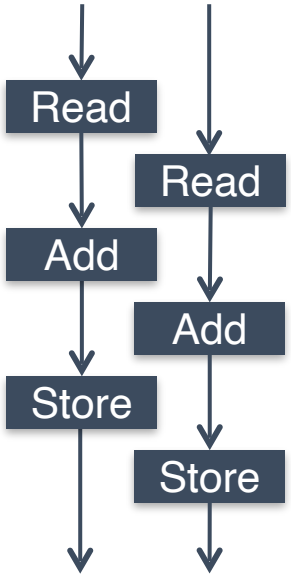

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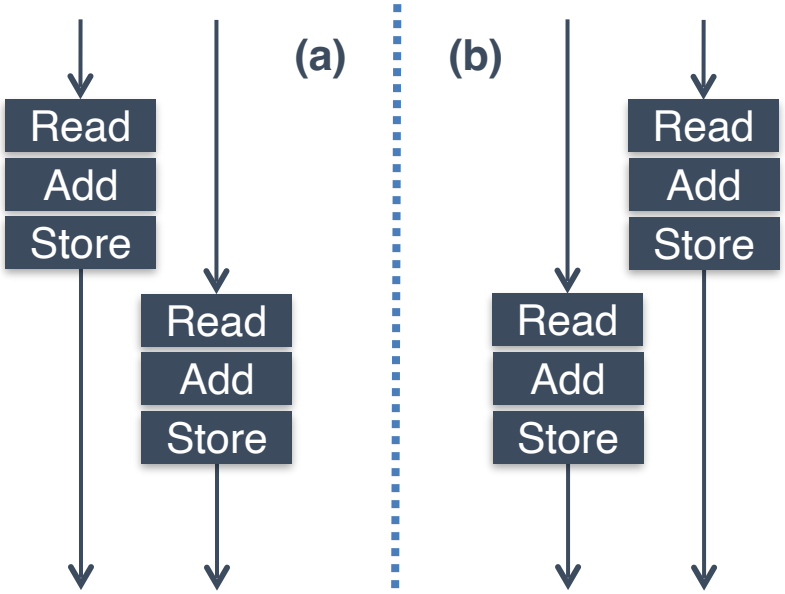

Non-Interleaved (Atomic) Execution

Locks

- **Locks**: enforces ***atomicity*** in code
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- Critical section: code block that requires mutual exclusion
  - Only one thread at a time can execute in the critical section
  - All other threads are forced to wait on entry
  - When a thread leaves a critical section, another can enter
  - Example: Banking application

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- *What requirements would you place on locks?*

Required Properties

1. Mutual exclusion
   - No two tasks may be simultaneously in critical sections accessing the same shared resource
2. Progress
   - If there is at least one process in a trying state, then eventually some process enters the critical section
3. Bounded waiting (no starvation)
   - Waiting time for a task to enter its critical section should be bounded

Using Locks

```
withdraw (account, amount) {
    acquire(lock);
    local var = get_balance(account);
    var = var – amount;
    put_balance(account, var);
    release(lock);
    return var;
}
```

Critical section

Thread A

```
acquire(lock);
local var = get_balance(account);
balance = var – amount;
```

Thread B: *wait for lock*

```
acquire(lock);
```

```
put_balance(account, var);
release(lock);
```

```
local var = get_balance(account);
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```

Implementing Locks

- Typically, developers don't write their own locking-primitives
  - You use an API from the OS or a library
- Why don't people write their own locks?
  - Much more complicated than they at-first appear
  - Very, very difficult to get correct
  - May require access to privileged instructions
  - May require specific assembly instructions
    - Instruction architecture dependent

Lock-based synchronization

- Low-level synchronization primitives
  - Primitive, minimal semantics, used to build others
  1. Disabling interrupts
     - Prevent context switches in single-core systems
  2. Hardware atomic instructions (spinlock)
     - Using test-and-set, compare-and-swap instructions
  3. Software-only solutions (spinlock)
     - Dekker's algorithm, Peterson's algorithm, …
- High-level synchronization methods
  - Operation System (& Programming Language) solutions
    - Sleeping & queues to avoid starvation, priority inheritance, etc.
  - Provide some functions and data structures to the programmer
    - Semaphore, monitor, …

Disabling Interrupts

- Enabling mutual exclusion by disabling interrupts
  - Prevent preemption/context switching
  - Example: implemented by cli or sti instruction (in x86)

```
struct lock {
}
void acquire (lock) {
    disable interrupts;
}
void release (lock) {
    enable interrupts;
}
```

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- Problems
  - Only available to kernel (why?)
  - What if the critical section is long?
    - Mutual exclusion is preserved but efficiency of execution is degraded
    - Can miss or delay important events
  - Works only on a single processor (how about multi-core?)
  - Not a general solution to use
    - Used to implement higher-level synchronization primitives as with spinlocks

Instruction-level Atomicity

- Modern CPUs have atomic instruction(s)
  - Enable you to build high-level synchronized objects

- Example: test-and-set instruction
  - Write (set) 1 to a memory location and return its old value as a single atomic (i.e., non-interruptible) operation
  - The caller can then "test" the result to see if the state was changed by the call

Using Test-And-Set

- Spin lock implementation with test-and-set:

```
struct lock {
    int held = 0;
}
void acquire (lock) {
    while (test-and-set(&lock->held) == 1);
}
void release (lock) {
    lock->held = 0;
}
```

Write 1 to the memory location and return its old value atomically

- When will the while return? What is the value of 'held'?

Using Test-And-Set

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```

Write 1 to the memory location and return its old value atomically

No bounded waiting (potential starvation)

- When will the while return? What is the value of 'held'?

The Price of Atomicity

- Atomic operations are very expensive on a multi-core system
  - Caches must be flushed
    - CPU cores may see different values for the same variable if they have out-of-date caches
    - Cache flush can be forced using a *memory fence* (sometimes called a *memory barrier*)
  - Memory bus must be locked
    - No concurrent reading or writing
  - Other CPUs may stall
    - May block on the memory bus or atomic instructions

Notes on spin-based locks

- Good for **short** critical sections
- Potentially, waste of resources
  - Spinning wastes processor cycles and can increase contention for the lock
  - The longer the critical section, the longer the spin
- Used as building block
  - Use spinlock as primitives to build high-level synchronization constructs
  - Mutex, semaphore: suspension-based (blocking) locks
    - Overhead can be larger than spinlocks. Why?
  - Monitor, conditional variables, etc.

Semaphores

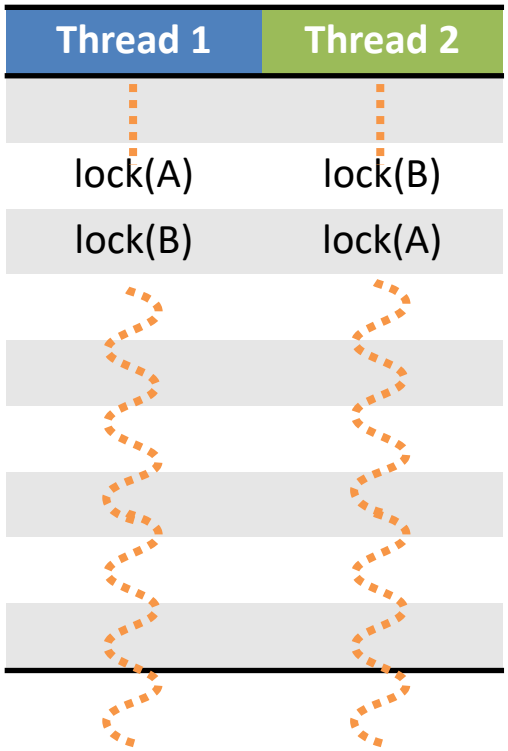
- Block waiters & leave interrupts enabled inside the critical section
  - Associated with a positive integer N (locked by up to N threads)
- wait(s): block until semaphore s is open; also called P()
- signal(s): allow another to enter; also called V()

```
semaphore s = 1; // binary semaphore; also called mutex
void wait (s) { // lock
   while (s <= 0) sleep;
   s--;
}
void signal (s) { // unlock
   s++;
   if (s > 0) wake up a waiter;
}
```

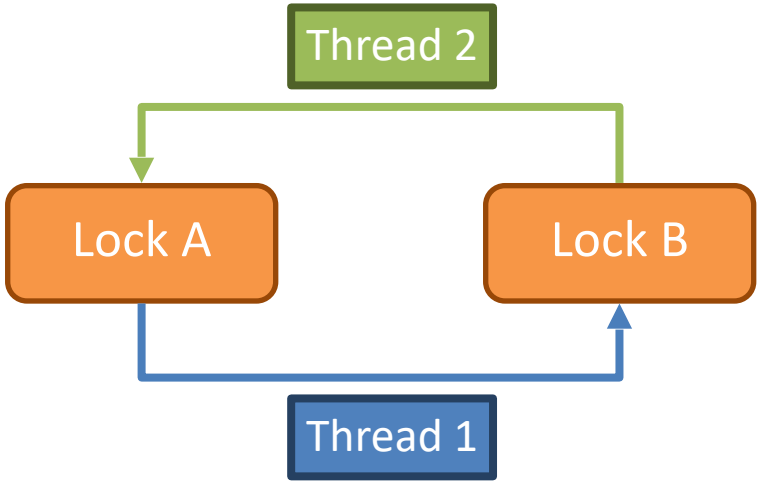
When Can Deadlocks Occur?

- Classic conditions for deadlock
  1. Mutual exclusion: resources can be exclusively held by one process
  2. Hold and wait: A process holding a resource can block, waiting for another resource
  3. No preemption on resource: one process cannot force another to give up a resource
  4. Circular wait: given conditions 1-3, if there is a circular wait then there is potential for deadlock
- Another issue:
  5. Buggy programming: programmer forgets to release one or more resources

Circular Waiting



- Simple example of circular waiting
  - Thread 1 holds lock *a*, waits on lock *b*
  - Thread 2 holds lock *b*, waits on lock *a*



Avoiding Deadlock

- If circular waiting can be prevented, no deadlocks can occur
- Technique to prevent circles: lock ranking
  1. Locate all locks in the program
  2. Number the locks in the order (rank) they should be acquired
  3. Add assertions that trigger if a lock is acquired out-of-order
- No automated way of doing this analysis
  - Requires careful programming by the developer(s)

Lock Ranking Example

	Thread 1	Thread 2
#1: mutex A #2: mutex B	lock A assert(islocked(A)) lock B // do something unlock B unlock A	assert(islocked(A)) lock B lock A // do something unlock A unlock B

- Rank the locks
- Add assertions to enforce rank ordering
- In this case, Thread 2 assertion will fail at runtime

Read Copy Update

Review: Lock-based synchronization

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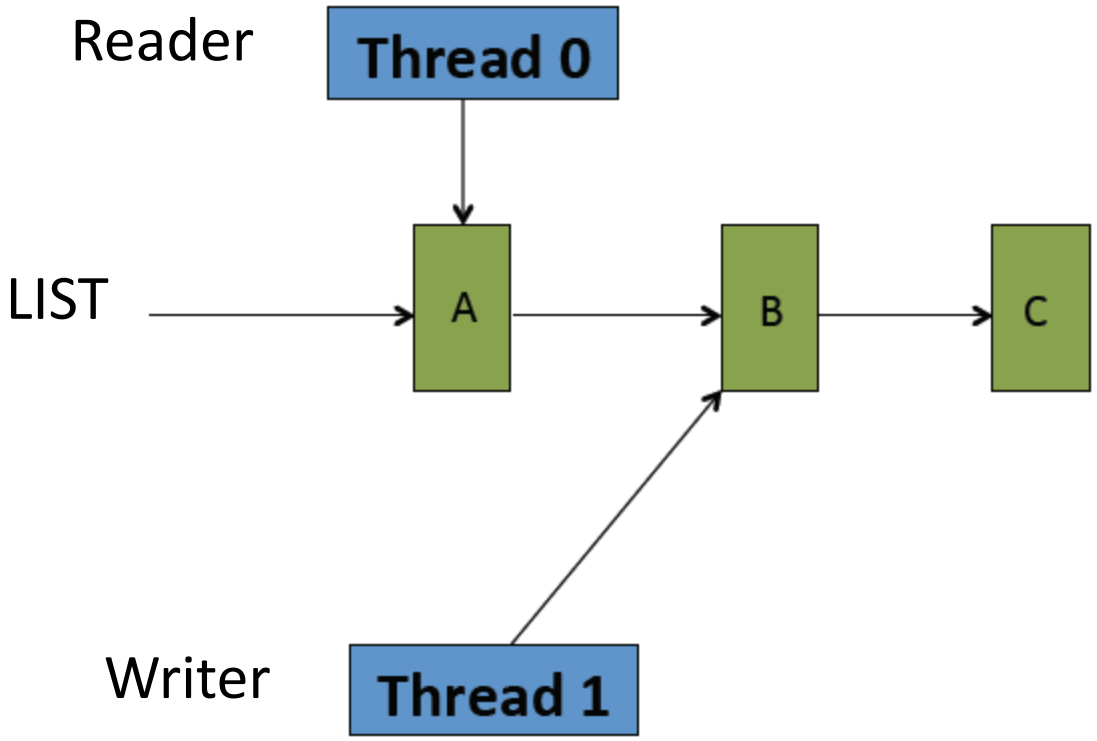
Traditional OS locking designs

- Poor concurrency
  - Accesses to critical sections are serialized
- Locks have acquire and release cost
  - Each uses atomic operations which are expensive
  - Can dominate cost for short critical regions
  - Locks become the bottleneck
  - Other issues: deadlocks and priority inversion
- Common pattern in OS kernel
  - A lot of reads
  - Writes are rare
  - Ok to read a slightly stale copy
    - But that can be fixed too

Mutex/Semaphore example

- A singly linked-list



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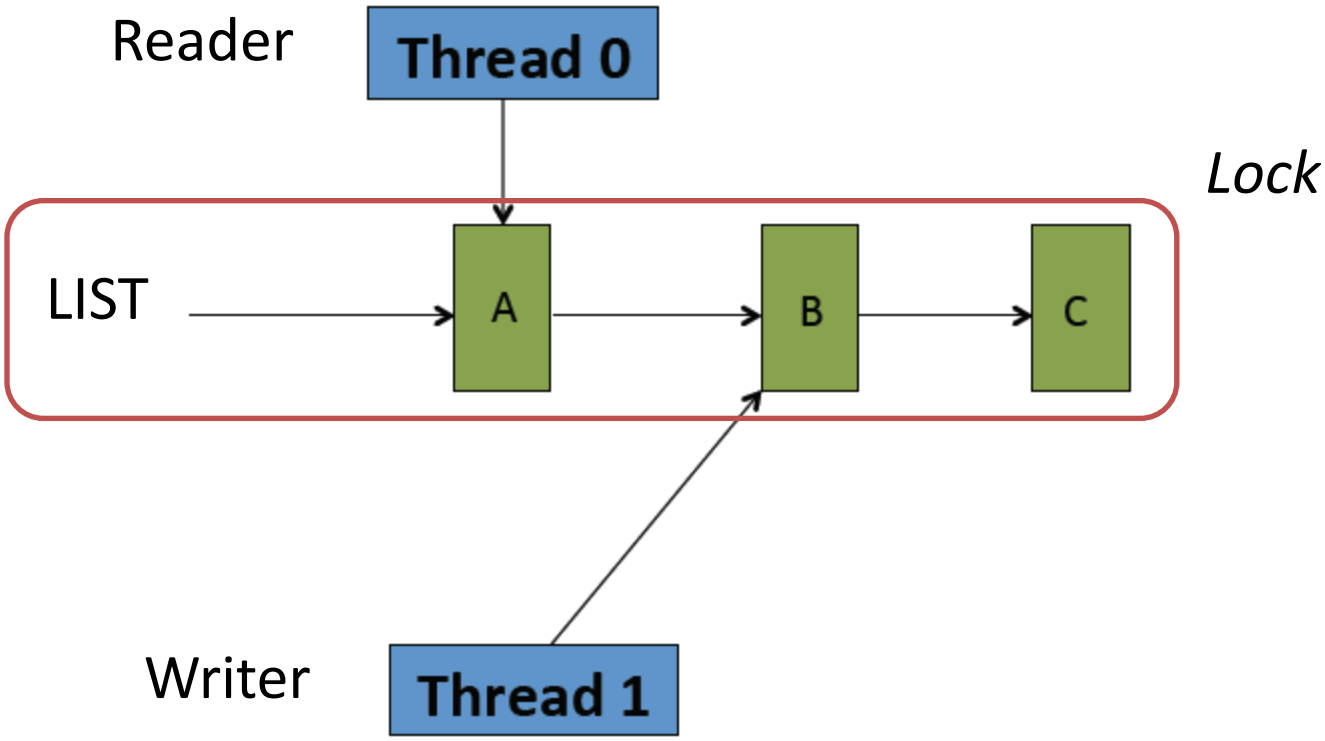

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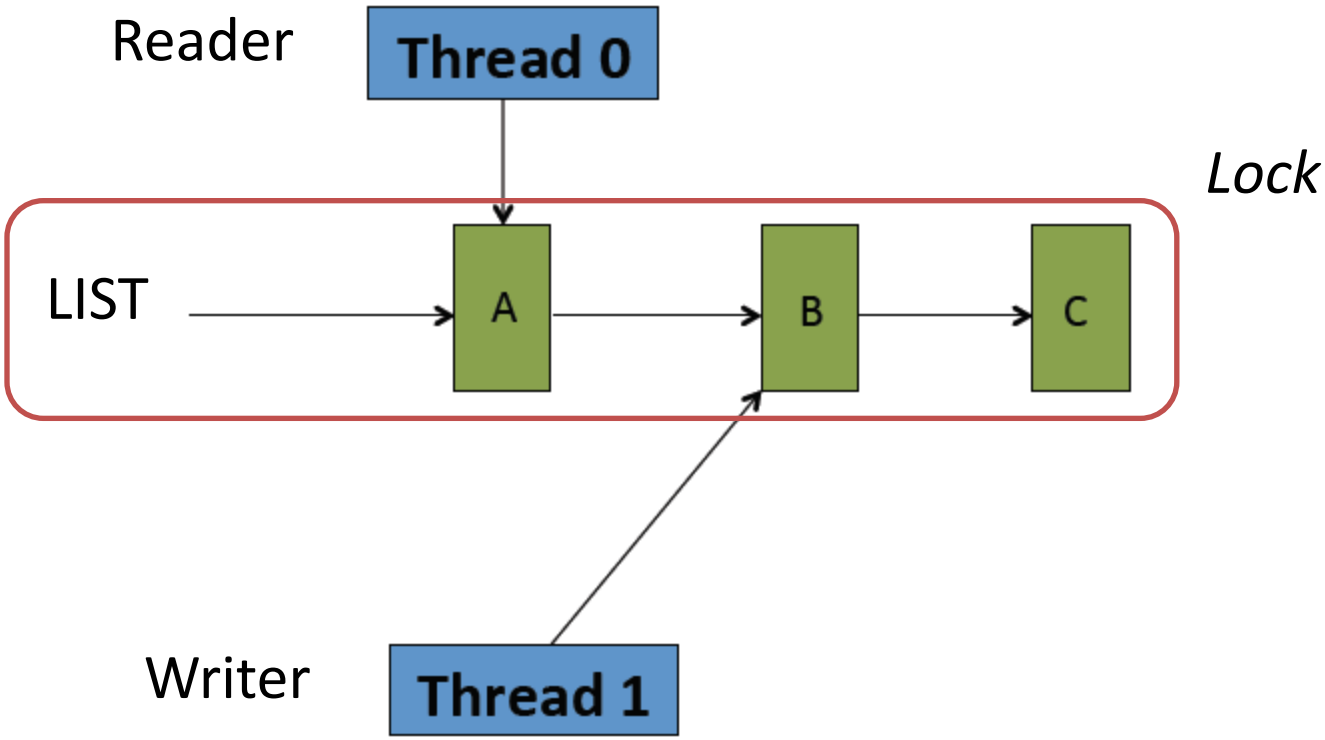
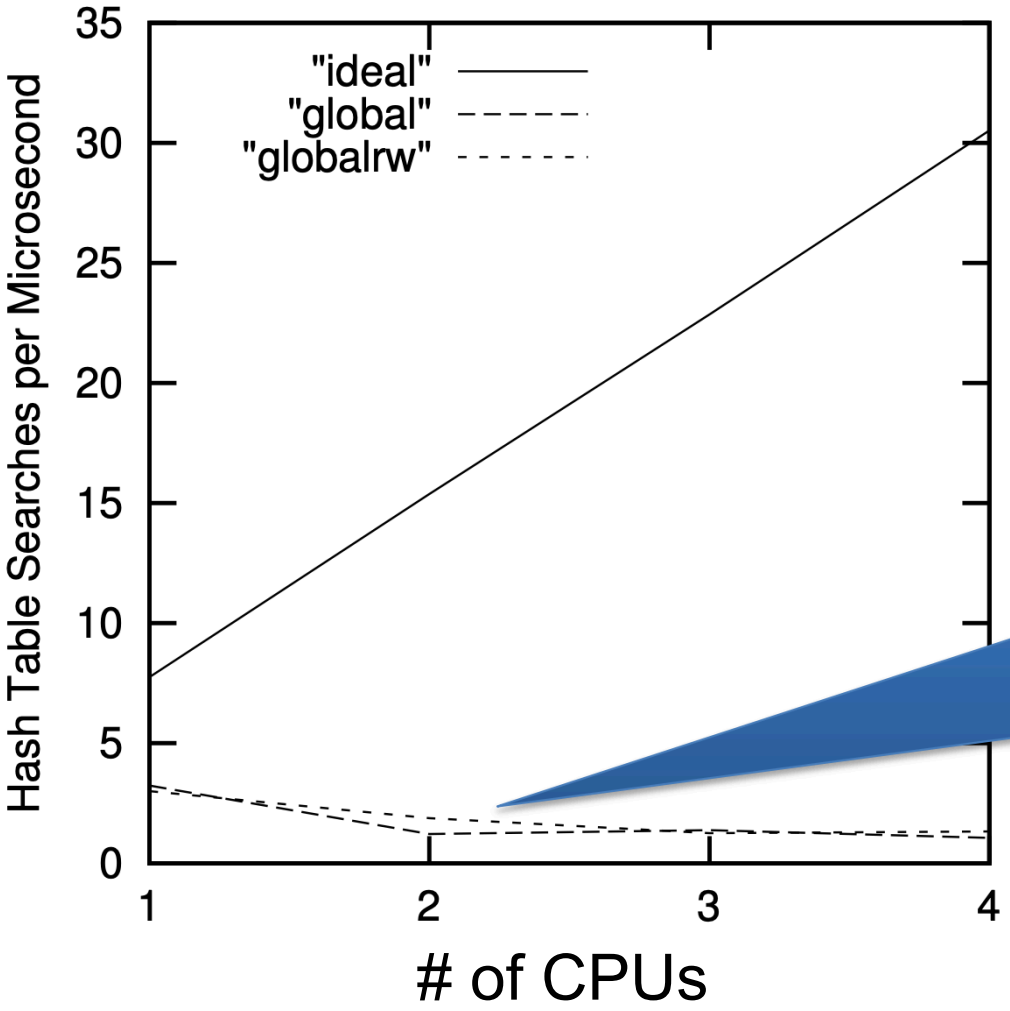


May be inefficient if it is mostly read only...

RW Locks: R/W problem

- Consider a shared database with readers & writers
  - Using a single lock is clearly inefficient
  - Like to have multiple readers at the same time & only one writer at a time
- First R/W problem (favoring reader):
  - No reader will wait even if a writer is waiting
  - Writer starvation!
  - Solutions: semaphore (mutex used to lock CS for R/W; binary Wrt lock used to block writers from entering the CS; read count lock used to count # of readers in CS and permits writer to enter when it becomes 0)
- Second R/W problem (favoring writer):
  - No new readers allowed once a writer has asked for access

Motivation behind RCU (from Paul McKenney's Thesis)



Performance of RW lock only marginally better than mutex lock

Reader-Writer Locks Limitation

- Locks have an acquire and release cost
  - Expensive atomic operations
  - May dominate performance, particularly for short critical sections
- Reader/writer locks may allow critical sections to execute in parallel
  - Still, need to serialize the increment and decrement of the read count with atomic instructions
  - Atomic instructions performance decreases as more CPUs try to do them at the same time
- The read lock itself becomes a major scalability bottleneck
- R/W lock still requires that writers wait for readers to finish

Lock-free data structures

- Do not require locks
- Good if contention is rare
- But difficult to create and error prone

- RCU (Read-Copy Update)
  - Useful for read-mostly data structures (rare writes)
  - Read is what readers do & Copy update is what writers do
  - Replace locking in time vs. locking in space
    - Writer creates a copy (new version) of data structure offline
    - Then swaps in the new version atomically
  - RCU serializes writers using locks
    - Win if most of our accesses are reads

RCU is *not* a lock

- Readers read latest published data
  - Readers are block-free
  - No deadlock
- Writers update on a copied data and publish the new version
  - Update without blocking (if there is one writer at a time)
  - Existing readers can continue with older version
- Need garbage collection for old versions of data
- Represents a way of thinking more than a specific algorithm

RCU Example

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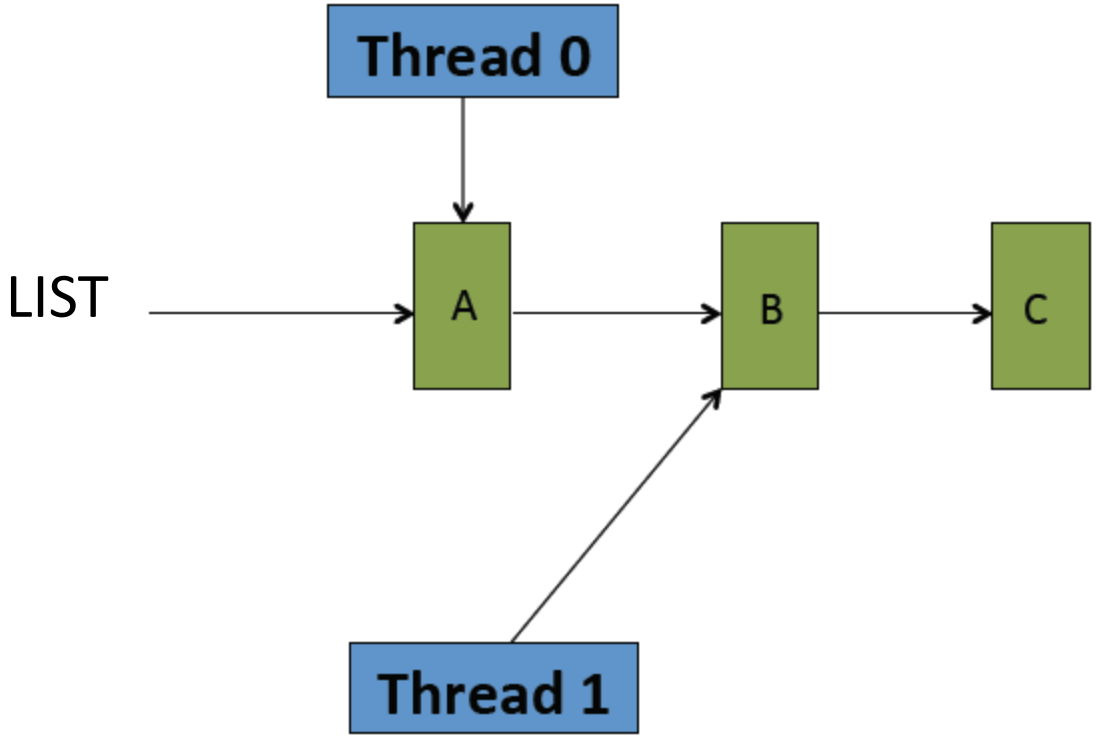

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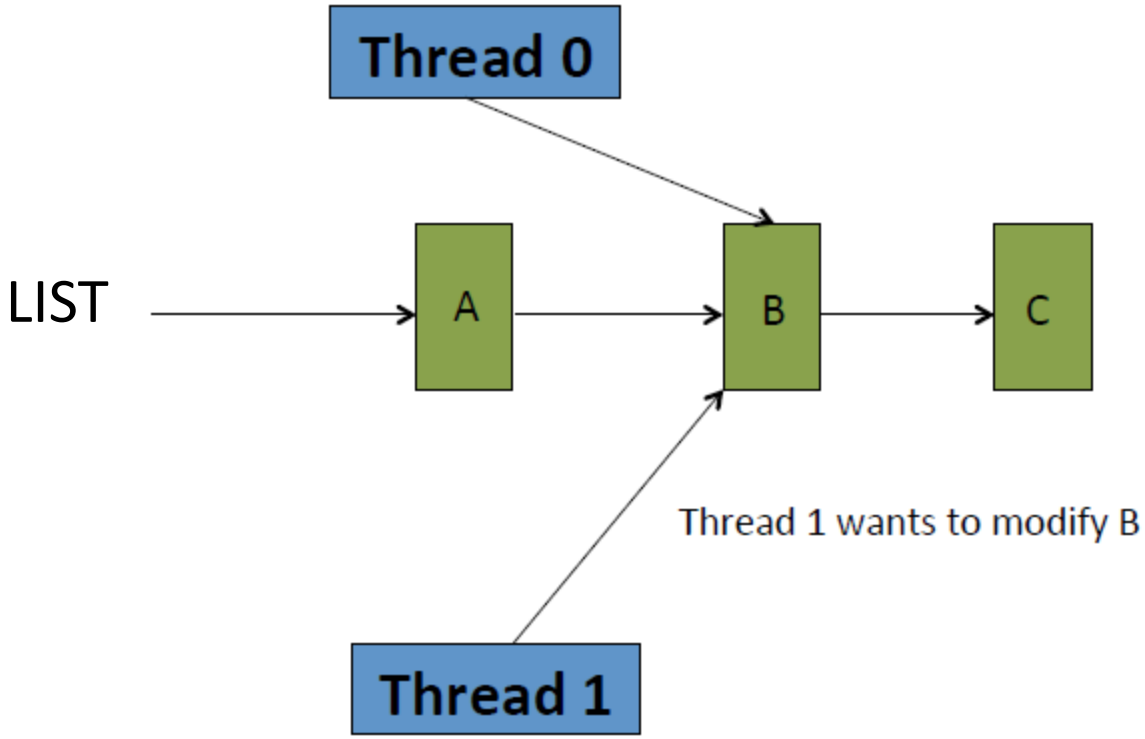

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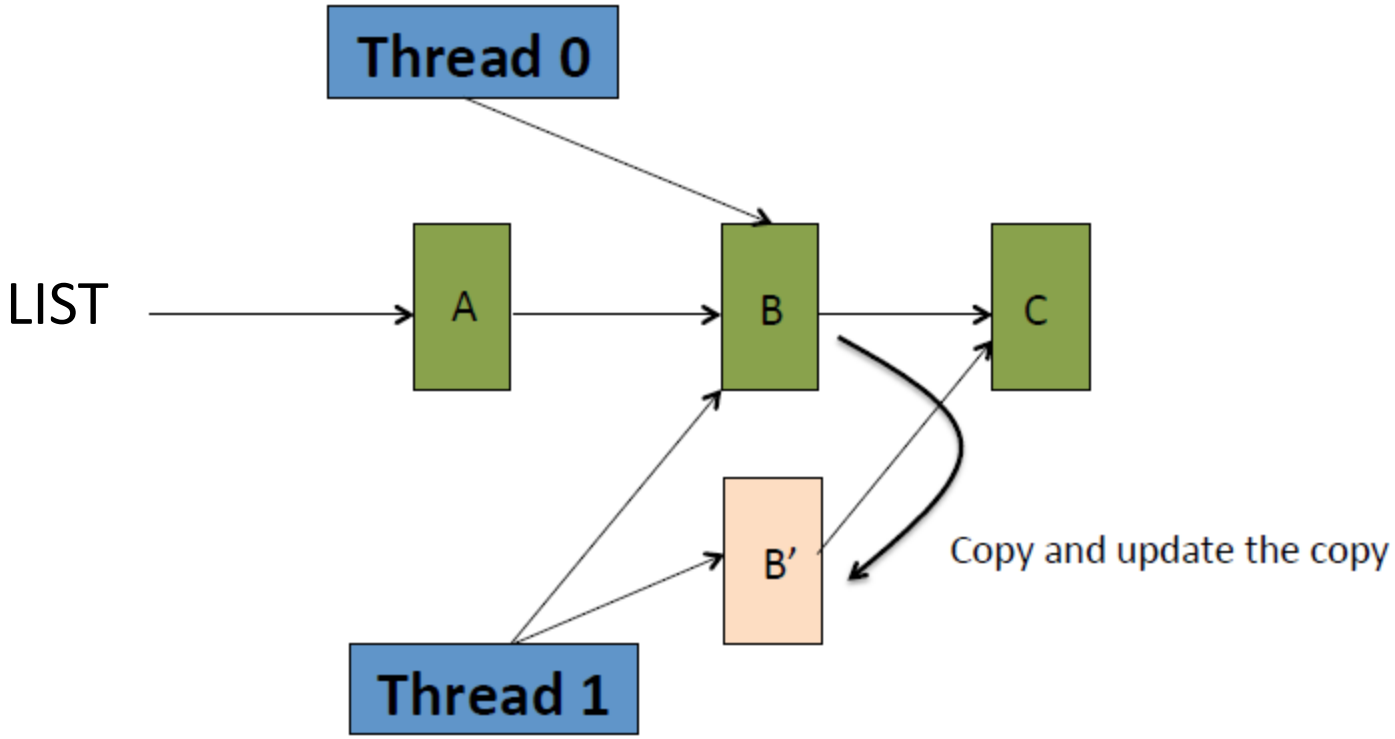

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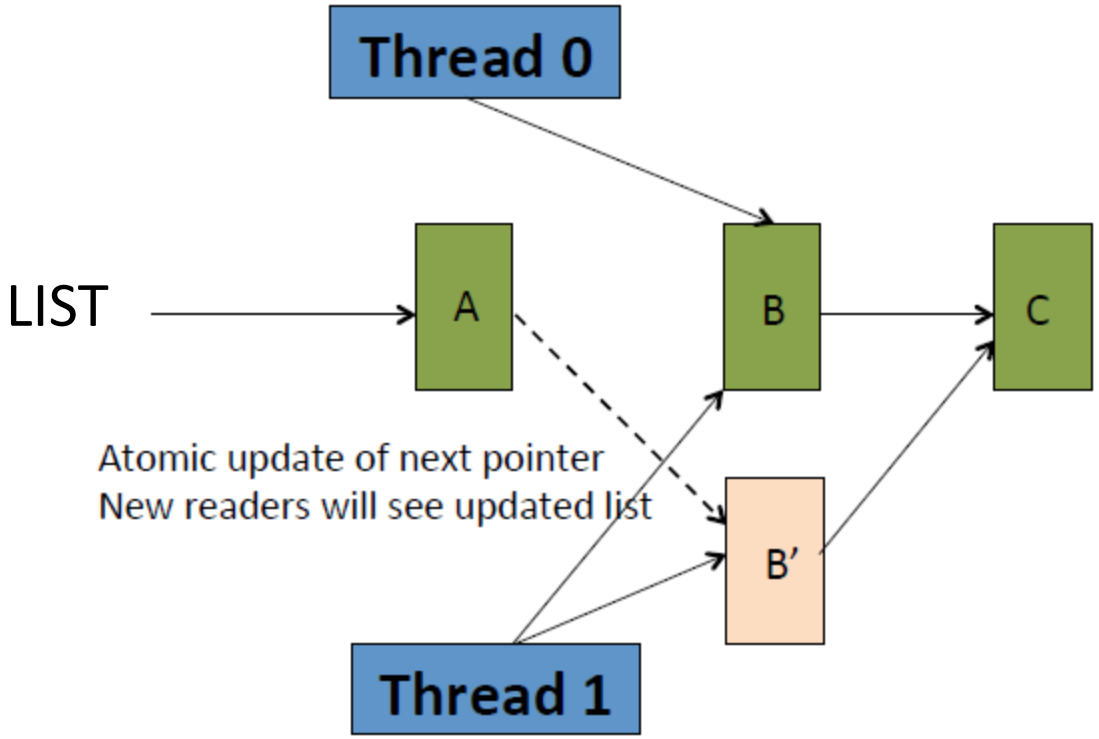

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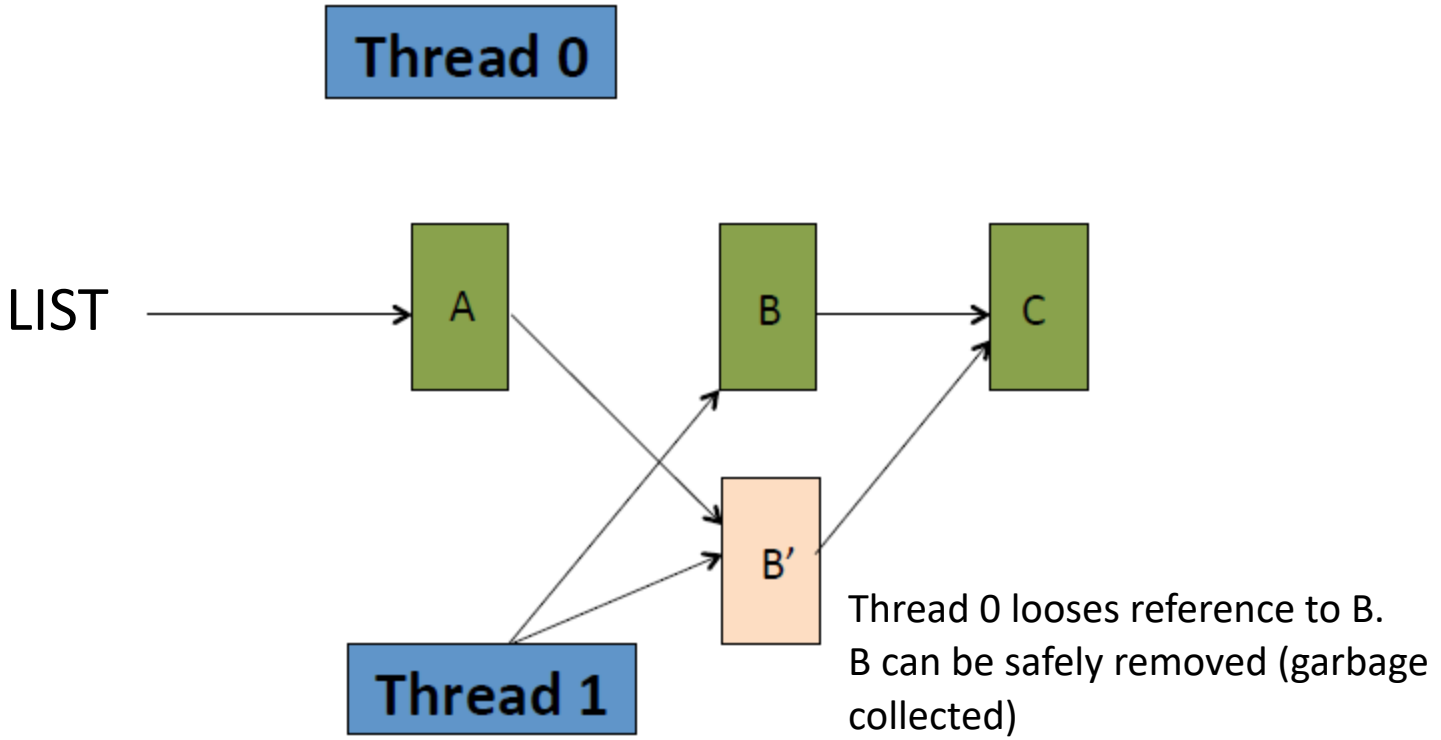
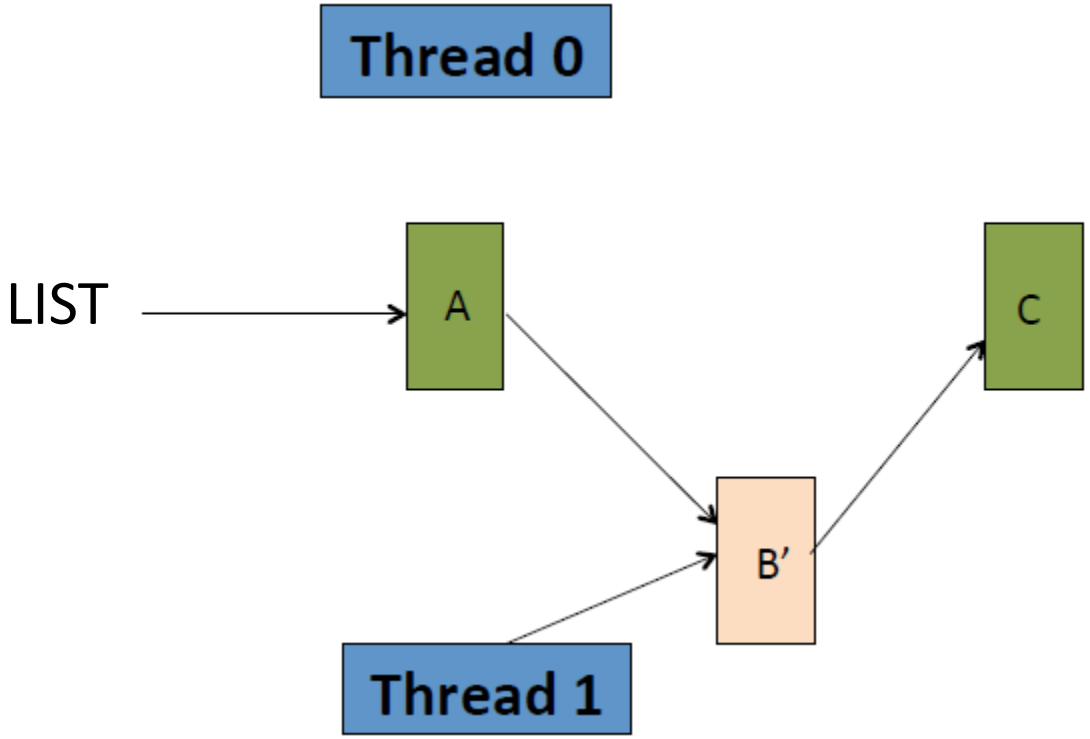


RCU Example

- A singly linked-list

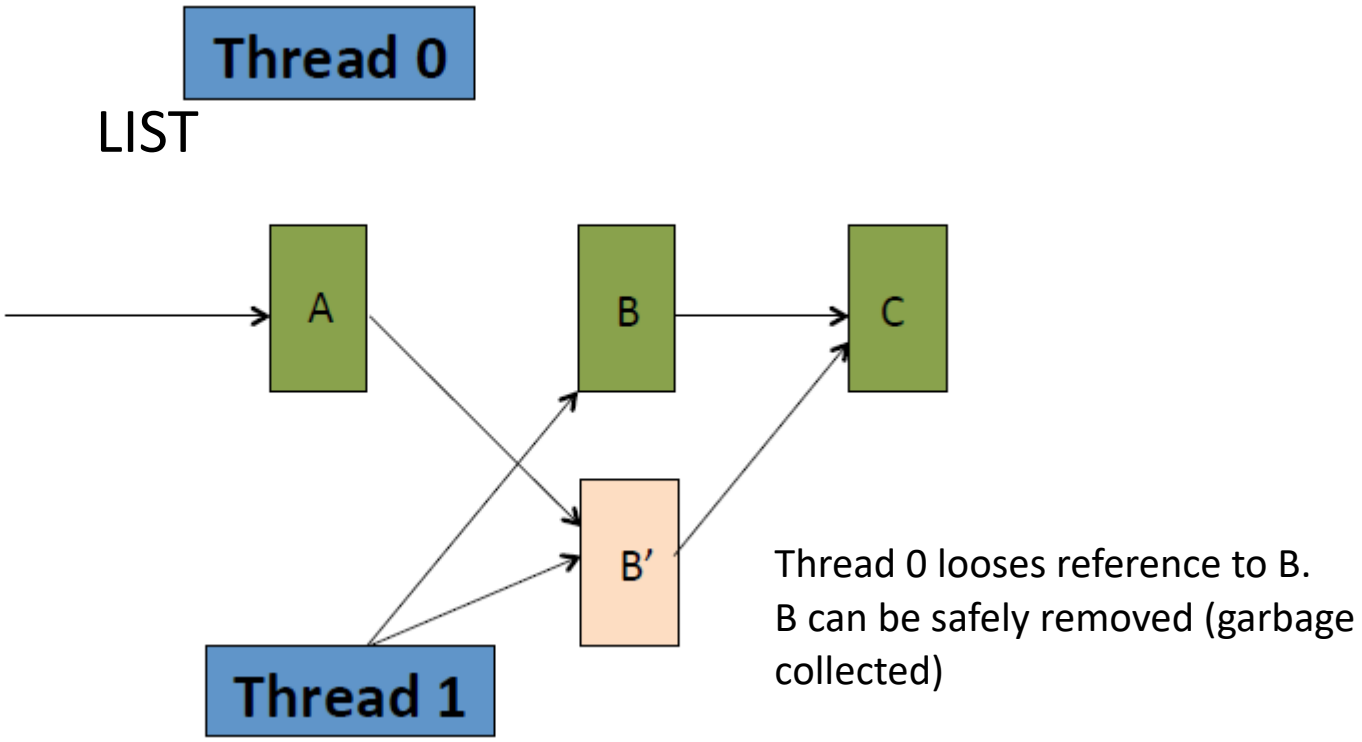


Challenges under lock-free algorithms

- One of the hardest parts of lock-free algorithms, including RCU, is concurrent changes to pointers
  - So just use locks and make writers go one at a time
- But, make writers be a bit careful so readers see a consistent view of the data structures
  - If 99% of accesses are readers, avoid performance-killing read lock in the common case

RCU Example

- Key idea: Carefully update the data structure so that a reader can never follow a bad pointer



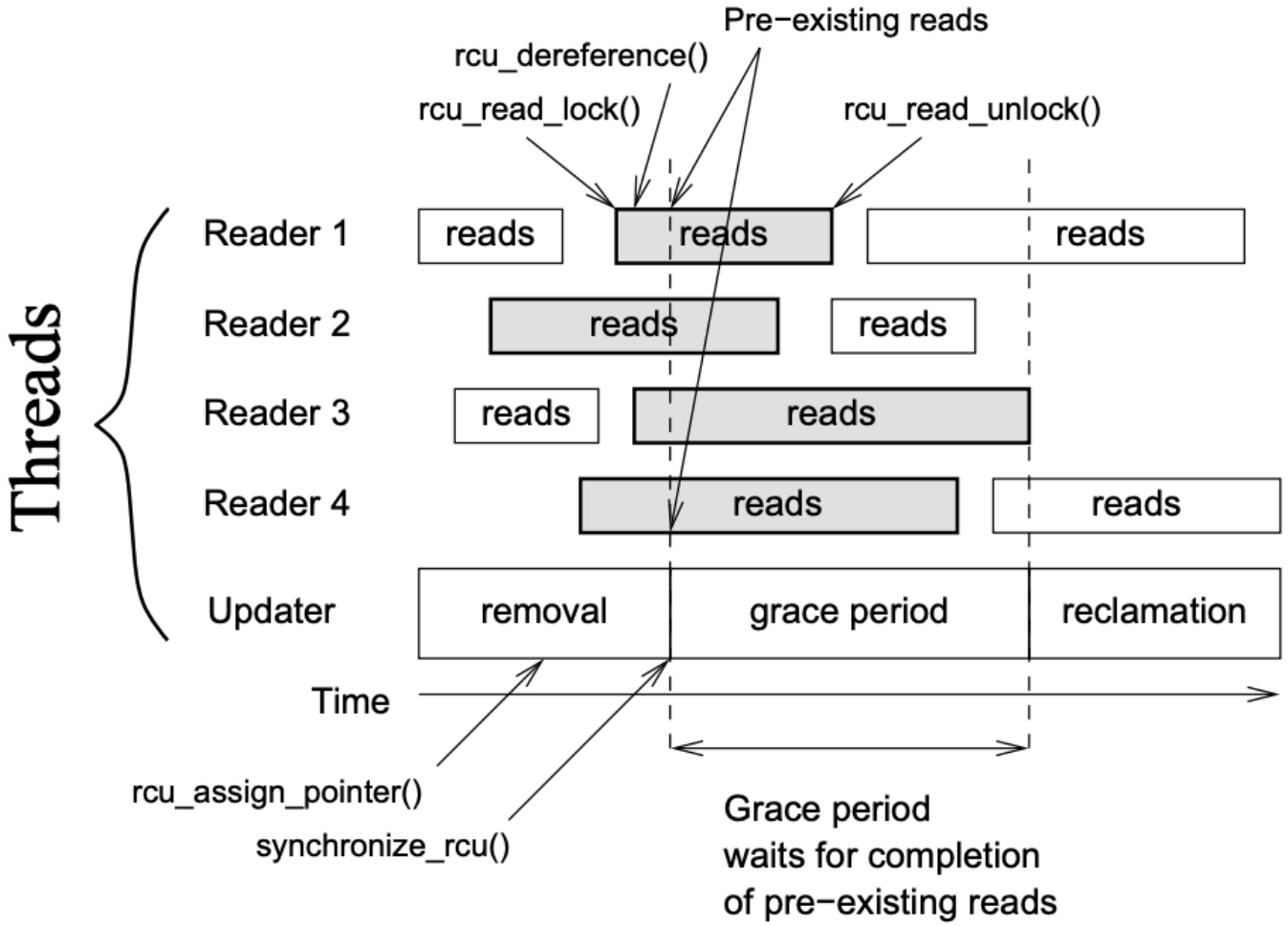
Garbage Collection

- Part of what makes this safe is that we don't immediately free node B
  - A reader could be looking at this node
  - If we free/overwrite the node, the reader tries to follow the 'next' pointer!
- How do we know when all readers are finished using it?
  - Hint: No new readers can access this node: it is now unreachable

Grace Period

- Reference counting:
  - RCU employs reference counting to track how many readers are currently in their read-side critical sections
- Grace Period:
  - After a writer thread updates the shared data structure, it initiates a "grace period."
  - The grace period is a period of time or a specific event during which RCU ensures that no new readers enter their read-side critical sections
  - The writer waits until the grace period is over.
- Reference Count Decrement:
  - After the grace period has passed, no new readers are allowed to enter their critical sections
  - The reference counter is decremented as readers exit their critical sections
- Reclamation of Old Version:
  - Safe when the reference counter associated with the old version of the data structure drops to zero

Grace Period



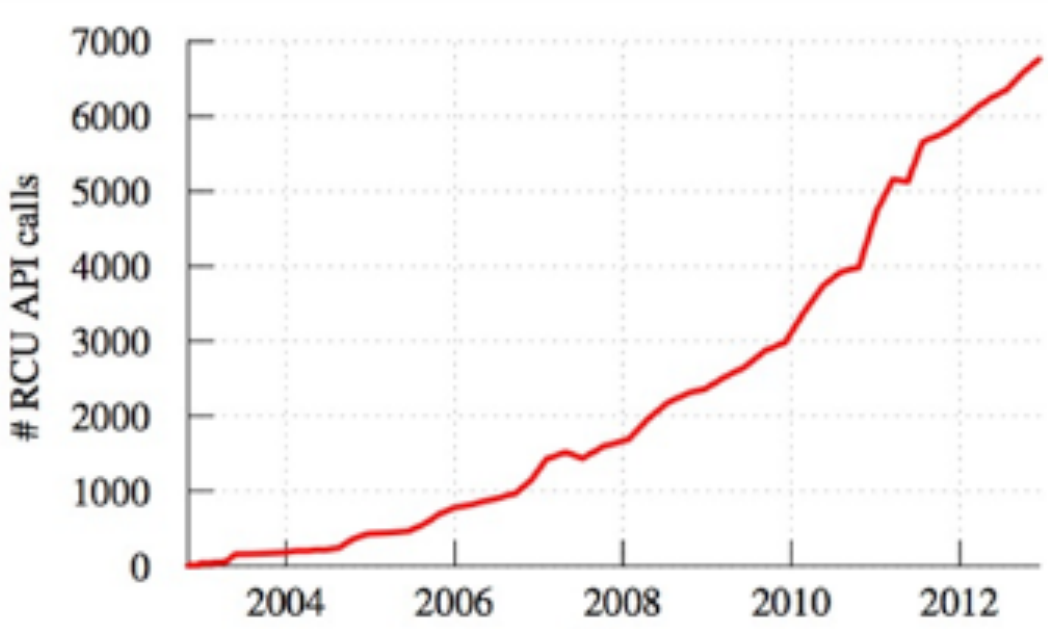
RCU Applicability

- Only a few RCU data structures in existence
  - Can RCU handle a doubly-linked list?
- Works well for singly-linked lists
  - Linked lists are the workhorse of the Linux kernel

RCU performance

- Significantly better performance in settings with many readers and few writers
- Performance highly depending on specific use cases and implementation details
  - E.g., R/W locks performs better when there are many writers

RCU usage in Linux ((from Paul McKenney)



RCU Pros and Cons

- Pros
  - Readers never block
  - Updates never block
  - Extremely scalable for large number of cores
  - No deadlocks
- Widely used in Linux kernel for scalability

RCU Pros and Cons

- Cons
  - Still need to synchronize multiple concurrent writers
  - Need to maintain multiple versions – can get complex
  - A lot of implementations do not support multiple writers, even if those writers work on different parts of data without blocking each other
- Research built upon RCU
  - RCU is just the beginning
  - RLU: read log update allows multiple changes to a data to be combined into a transaction which is not seen by any reader until completion
  - Transactional memory
    - Transparently support regions of code marked as transactions by enforcing atomicity, consistency, and isolation