CONCURRENT ACCESS TO SHARED DATA STRUCTURES

CS124 – Operating Systems

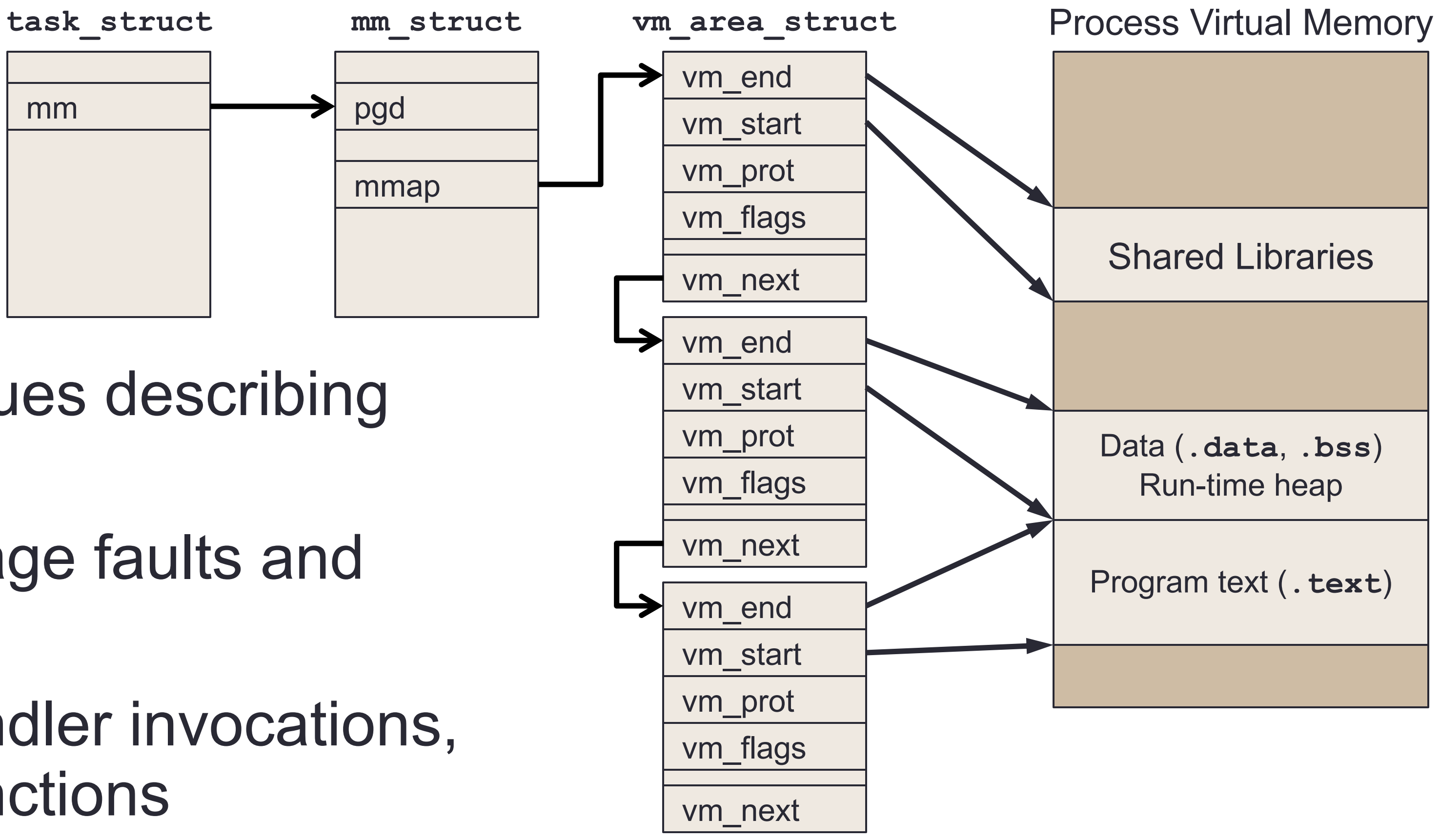
Spring 2024, Lecture 10

Last Time: Synchronization

- Last time, discussed a variety of multithreading issues
    - Frequently have shared state manipulated by multiple threads
    - Usually solve this problem using some kind of mutual-exclusion mechanism, e.g. disabling interrupts, mutexes, semaphores, etc.
- Many examples of shared state within the OS kernel
    - Scheduler ready-queue, other queues (accessed concurrently on multicore systems)
    - Filesystem cache (shared across all processes on the system)
    - Virtual memory mapping (used by fault handlers and trap handlers)
- Frequently managed in linked lists (although other more sophisticated structures are often used)
- Frequently this state is read much more than it's written

Example: `vm_area_struct` Lists

- Example: vm_area_struct list used for process memory



- List nodes hold many values describing memory regions
- Mostly used to resolve page faults and protection faults
- Also modified by trap-handler invocations, e.g. **`mmap()`**, **`sbrk()`** functions

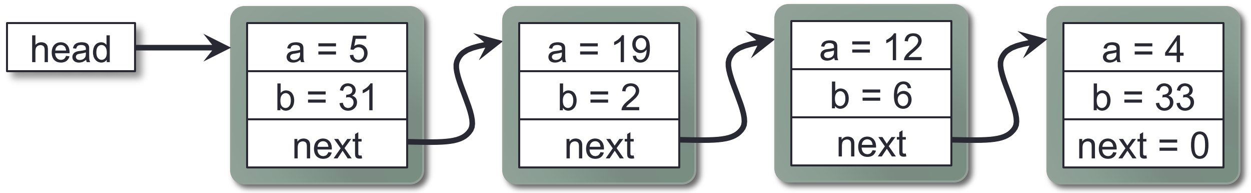
Example Problem: Linked Lists

- How would we implement a linked list that supports concurrent access from multiple kernel control paths?
- Consider a simplified list type:
  - Each element contains several important fields, and a pointer to next node in the list

```
typedef struct list_node {
  int a;
  int b;
  struct list_node *next;
} list_node;

list_node *head;
```

- Example list contents:



Example Problem: Linked Lists (2)

- Operations on our linked list:

- Iterate over the list nodes, examining each one
  - e.g. to find relevant data, or find a node that needs modified
- Insert a node into the linked list
- Modify a node in the linked list
- Remove a node from the linked list

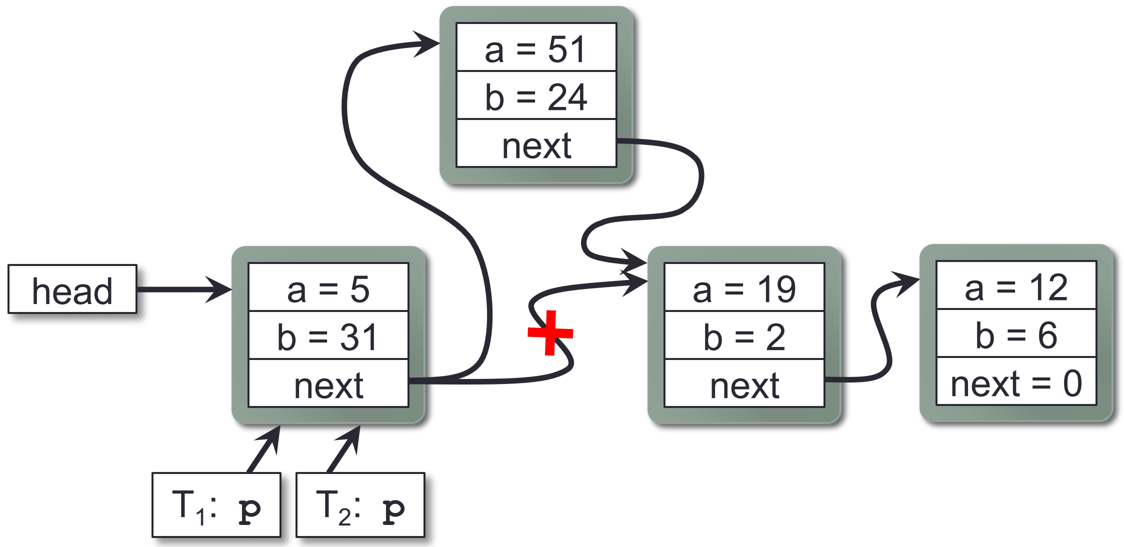
- All of these operations are straightforward to implement
  - Can imagine other similar operations, variants of the above

```
typedef struct list_node {
  int a;
  int b;
  struct list_node *next;
} list_node;

list_node *head;
```

Linked List and Concurrent Access

- Should be obvious that our linked list will be corrupted if manipulated concurrently by different threads
- Example:
  - One thread is traversing the list, searching for the node with **`a`** = 12, so it can retrieve the current value of **`b`**
  - Another thread is inserting a new node into the list

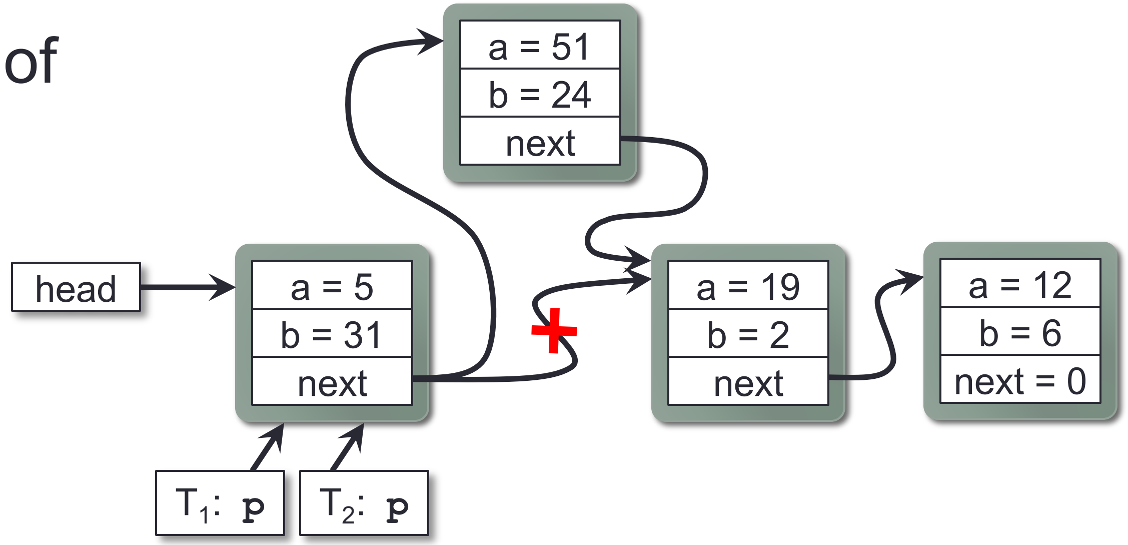


Linked List and Concurrent Access (2)

- This scenario can fail in many different ways
- Writer-thread T_2 must perform several operations:

```
list_node *new = malloc(sizeof(list_node));
new->a = 51;
new->b = 24;
new->next = p->next;
p->next = new;
```

- We can try to specify a reasonable order of operations in our code…
- Really have no guarantees about how the compiler will order this.
- Or the CPU, for that matter.

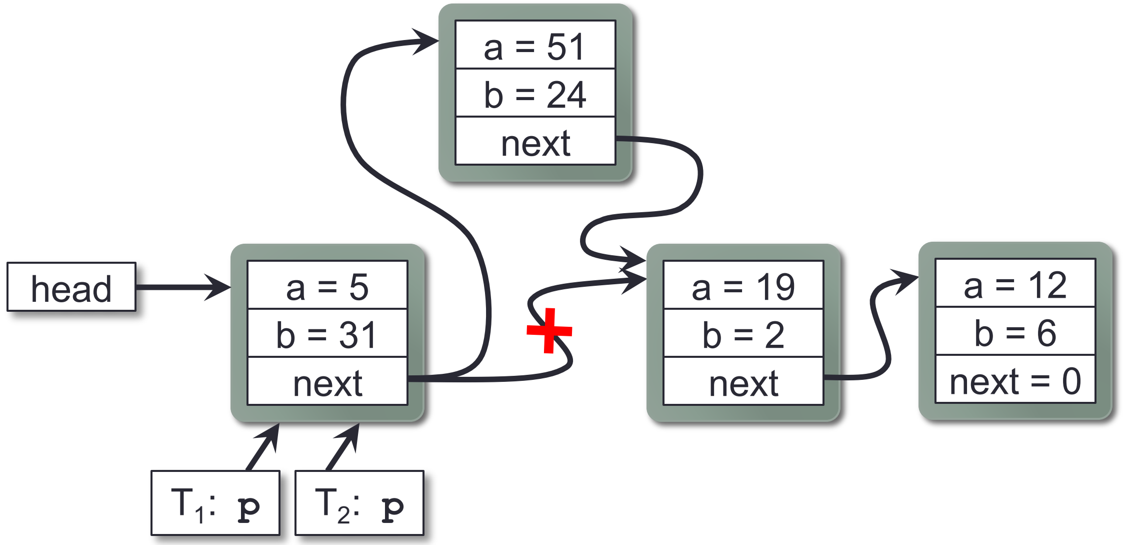


Linked List and Concurrent Access (3)

- Operations that writer-thread T_2 must perform:

```
list_node *new = malloc(sizeof(list_node));
new->a = 51;
new->b = 24;
new->next = p->next;
p->next = new;
```

- These operations form a critical section in our code
- Must enforce exclusive access to the affected nodes during these operations



Fixing Our Linked List

- **How do we avoid concurrency bugs in our linked list implementation?**
- An easy solution: use a single lock to guard the entire list
  - Any thread that needs to read or modify the list must acquire the lock before accessing **head**

```
typedef struct list_node {
  int a;
  int b;
  struct list_node *next;
} list_node;

list_node *head;
lock_t list_lock;
```

- Design this solution to work from multiple kernel control paths, e.g.
  - On a single-core system, trap handler and interrupt handlers simply disable interrupts while accessing the list
  - On a multi-core system, use a combination of spin-locks and disabling interrupts to protect access to the list

Fixing Our Linked List (2)

- **How do we avoid concurrency bugs in our linked list implementation?**
- An easy solution: use a single lock to guard the entire list
  - Any thread that needs to read or modify the list must acquire the lock before accessing **`head`**

```
typedef struct list_node {
  int a;
  int b;
  struct list_node *next;
} list_node;

list_node *head;
lock_t list_lock;
```

- *Why must readers also acquire the lock before reading??*
- Only way for the writer to ensure that readers won't access the list concurrently, while it's being modified ☹

Linked List: A Single Lock

- **What's the obvious issue with this approach?**
- Readers shouldn't ever block other readers
  - (we know the list is mostly accessed by readers anyway…)
  - It's okay if writers hold exclusive access to the list while modifying it
  - (it would be better if multiple writers could concurrently modify independent sections of the list)
- This approach has very high **lock contention**
  - Threads spend a lot of time waiting to acquire the lock, just to access the shared resource
  - <u>No</u> concurrent access is allowed to the shared resource

```
typedef struct list_node {
  int a;
  int b;
  struct list_node *next;
} list_node;

list_node *head;
lock_t list_lock;
```

Linked List: Improving Concurrency

- **Ideally, readers should <u>never</u> block other readers**
  - (for now, accept the behavior that writers block everybody)
- How can we achieve this?
- Can use a **read/write lock** instead of a mutex
  - Multiple readers can acquire <u>shared</u> access to the lock: readers can use the shared resource concurrently without issues
  - Writers can acquire <u>exclusive</u> access to the lock
- Two lock-request operations:
  - `read_lock(rwlock_t *lock)` – used by readers
  - `write_lock(rwlock_t *lock)` – used by writers

```
typedef struct list_node {
  int a;
  int b;
  struct list_node *next;
} list_node;

list_node *head;
rwlock_t list_lock;
```

Linked List: Read/Write Lock (2)

- Using a read/write lock greatly increases concurrency and reduces lock contention

```
typedef struct list_node {
  int a;
  int b;
  struct list_node *next;
} list_node;

list_node *head;
rwlock_t list_lock;
```

- **Still a few annoying issues:**
- Readers must still acquire a lock every time they access the shared resource
  - All threads incur a certain amount of **lock overhead** when they acquire the lock (in this case, CPU cycles)
  - This overhead can be *hundreds* of CPU cycles, even for efficient read/write locks

Linked List: Read/Write Lock (3)

- Using a read/write lock greatly increases concurrency and reduces lock contention

```
typedef struct list_node {
  int a;
  int b;
  struct list_node *next;
} list_node;

list_node *head;
rwlock_t list_lock;
```

- **Still a few annoying issues:**
- Also, writers still block everybody
- Can we find a way to manipulate this linked list that doesn't require writers to acquire exclusive access?

Linked List: Multiple Locks

- One approach for reducing lock contention is to decrease the **granularity** of the lock
    - i.e. how much data is the lock protecting?

```
typedef struct list_node {
  rwlock_t node_lock;
  int a;
  int b;
  struct list_node *next;
} list_node;

list_node *head;
```

- Idea: Introduce more locks, each of which governs a smaller region of data
- For our linked list, could put a read/write lock in each node
    - Threads must acquire many more locks to work with the list, which means that the locking overhead goes way up ☹
    - But, writers can lock only the parts of the list they are changing, which means we can reduce lock contention/increase concurrency

Skip to RCU

Linked List: Multiple Locks (2)

- We need one more read/write lock, to guard the **`head`** pointer
  - Need to coordinate accesses and updates of **`head`** so that a thread doesn't follow an invalid pointer!
  - If a thread needs to change what **`head`** points to, it needs to protect this with a critical section

```
typedef struct list_node {
  rwlock_t node_lock;
  int a;
  int b;
  struct list_node *next;
} list_node;

list_node *head;
rwlock_t head_lock;
```

- Now we have all the locks necessary to guard the list when it's accessed concurrently

Skip to RCU

Linked List: Multiple Locks (3)

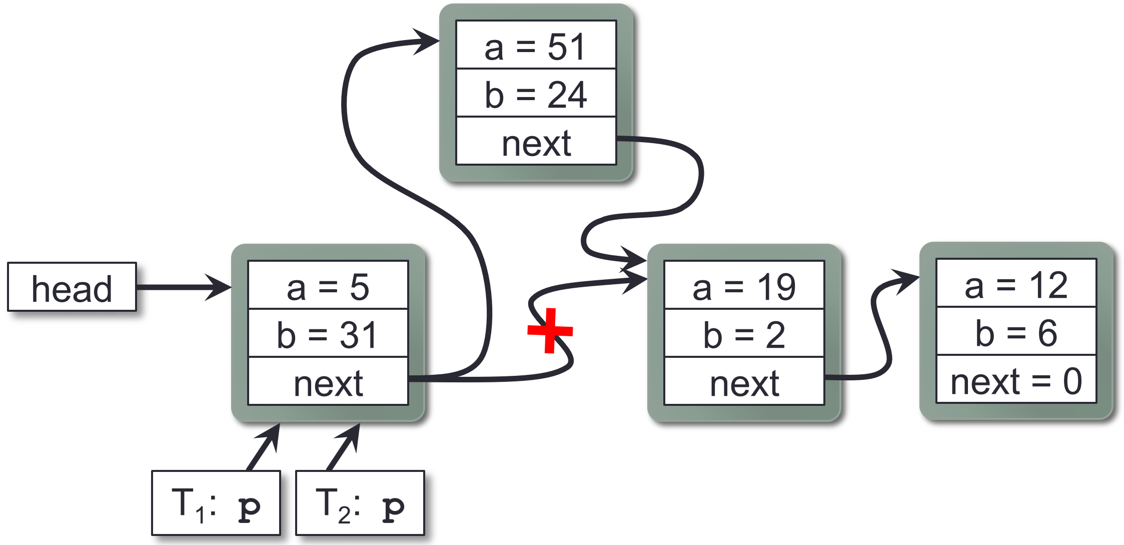
- **With multiple locks in our structure, we must beware of the potential for deadlock…**
- Can easily avoid deadlock by requiring that all threads lock nodes in the same total order
  - Prevent "circular wait" condition
- This is easy – it's a singly linked list! Always lock nodes in order from head to tail.
- This makes it a bit harder on writers
  - How does a writer know whether to acquire a read lock or a write lock on a given node?
  - Need to acquire a read lock first, examine the node, then release and reacquire a write lock if the node must be altered.

```
typedef struct list_node {
  rwlock_t node_lock;
  int a;
  int b;
  struct list_node *next;
} list_node;

list_node *head;
rwlock_t head_lock;
```

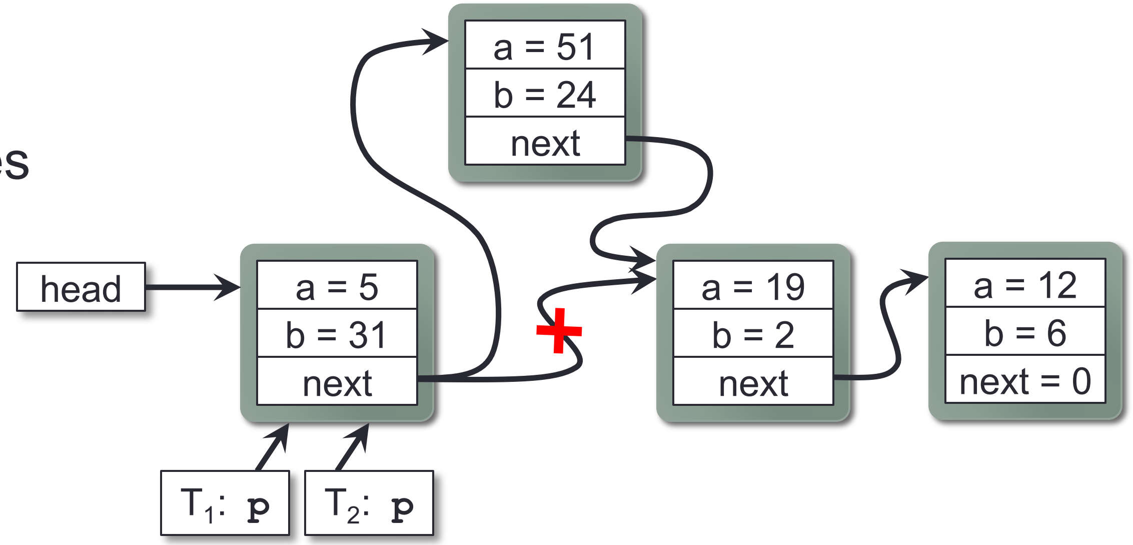
Linked List: Multiple Locks, Example

- T_1 acquires a read-lock on **`head`** so it won't change.
  - Then T_1 follows **`head`** to the first node, and acquires a read-lock on this node so it won't change.
  - *(and so forth)*
- This process of holding a lock on the current item, then acquiring a lock on the next item before releasing the current item's lock, is called **crabbing**
- As long as T_1 holds a read lock on current node, and acquires read-lock on next node before visiting it, it won't be affected by other threads



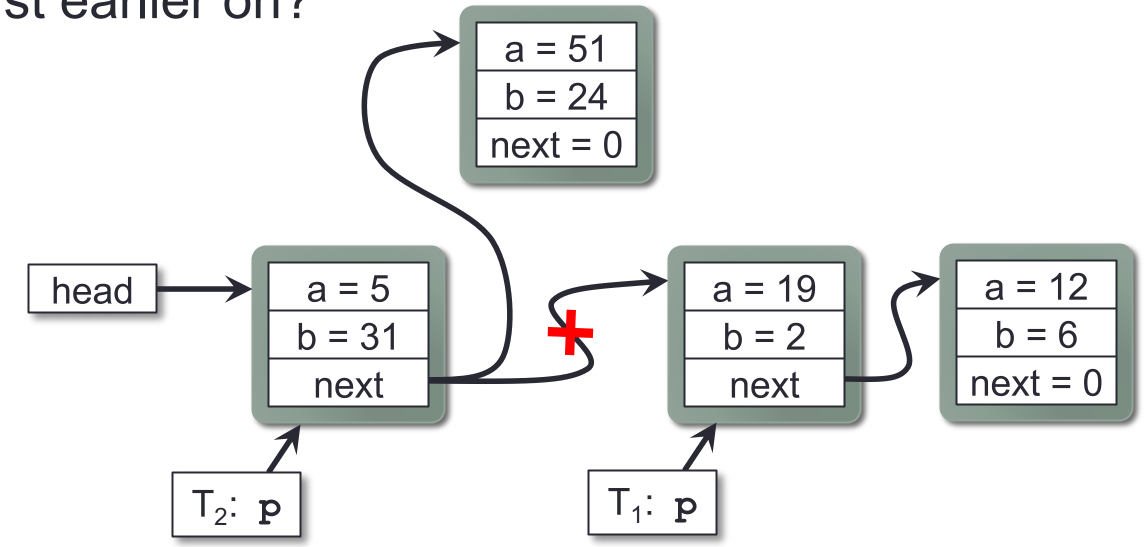
Linked List: Multiple Locks, Example (2)

- T_2 behaves in a similar manner:
  - T_2 acquires a read-lock on **`head`** so it won't change.
  - Then T_2 follows **`head`** to the first node, and acquires a read lock on this node so it won't change.
  - When T_2 sees that the new node must go after the first node, it can acquire a write-lock on the first node
    - Ensures its changes won't become visible to other threads until lock is released
  - After T_2 inserts the new node, it can release its locks to allow other threads to see the changes



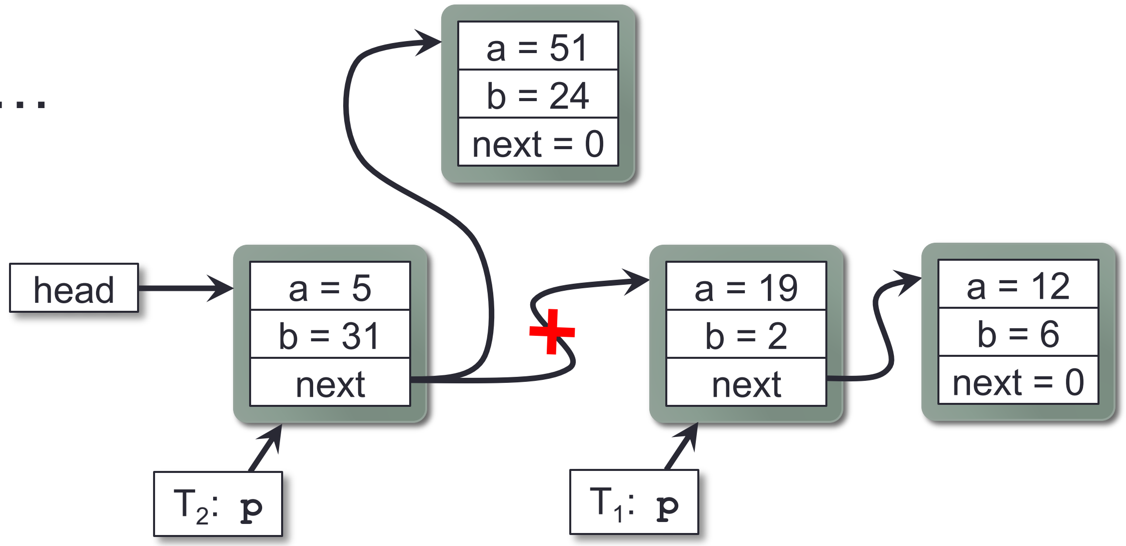
Linked List: Holding Earlier Locks

- A key question: **How long should each thread hold on to the locks it previously acquired in the list?**
- If a thread releases locks on nodes after it leaves them, then other threads might change those nodes
  - Does the thread need to be aware of values written by other threads, that appear earlier in the list?
  - What if another thread completely changes the list earlier on?
- If these scenarios are acceptable, then threads can release locks as soon as they leave a node
  - (Often, it's acceptable!)



Linked List: Holding Earlier Locks (2)

- A key question: **How long should each thread hold on to the locks it previously acquired in the list?**
- If such scenarios are unacceptable, threads can simply hold on to all locks until they are finished with the list
  - Ensures that each thread will see a completely consistent snapshot of the list until the thread is finished with its task
- Even simple changes in how locks are managed can have significant implications…



Lock-Based Mutual Exclusion

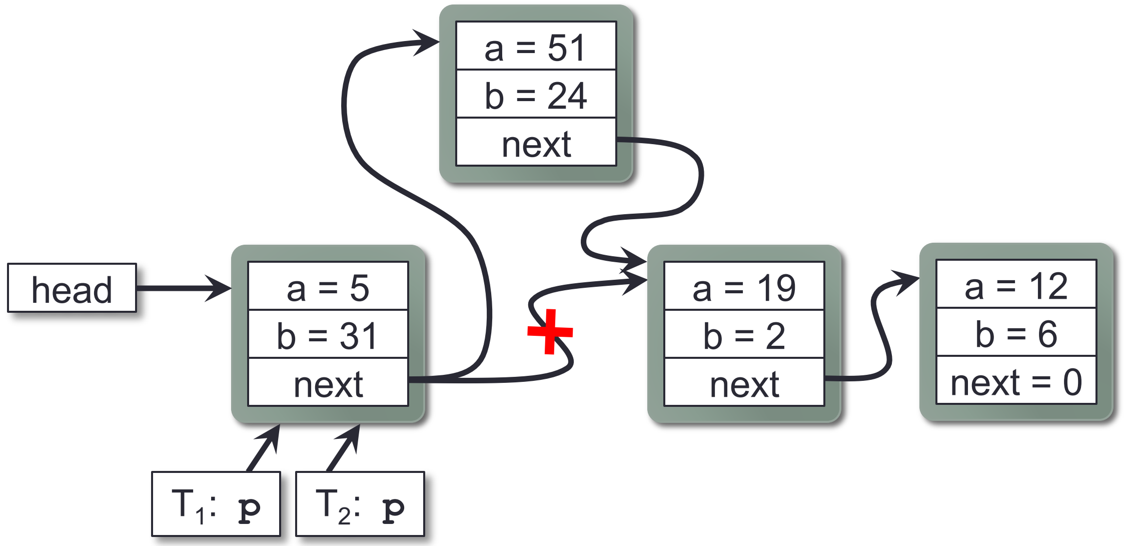
- **Lock-based approaches have a lot of problems**
- Have to make design decisions about what granularity of locking to use
  - Coarse-granularity locking = lower lock overhead, but writers block everyone
  - Fine-granularity locking = much higher lock overhead, but can achieve more concurrency with infrequent writers in the mix
- More locks means more potential for deadlock to occur
- Locks make us prone to other issues like priority inversion (more on this in a few lectures)
- Can’t use locks in interrupt context anyway, except in specific circumstances

Mutual Exclusion

- What is the fundamental issue we are trying to prevent?
  - Different threads seeing (or creating) inconsistent or invalid state
- Earlier example: writer-thread T_2 inserting a node

```
list_node *new = malloc(sizeof(list_node));
new->a = 51;
new->b = 24;
new->next = p->next;
p->next = new;
```

- A big part of the problem is that we can't guarantee the order or interleaving of these operations
  - Locks help us to sidestep this issue by guarding *all* the operations

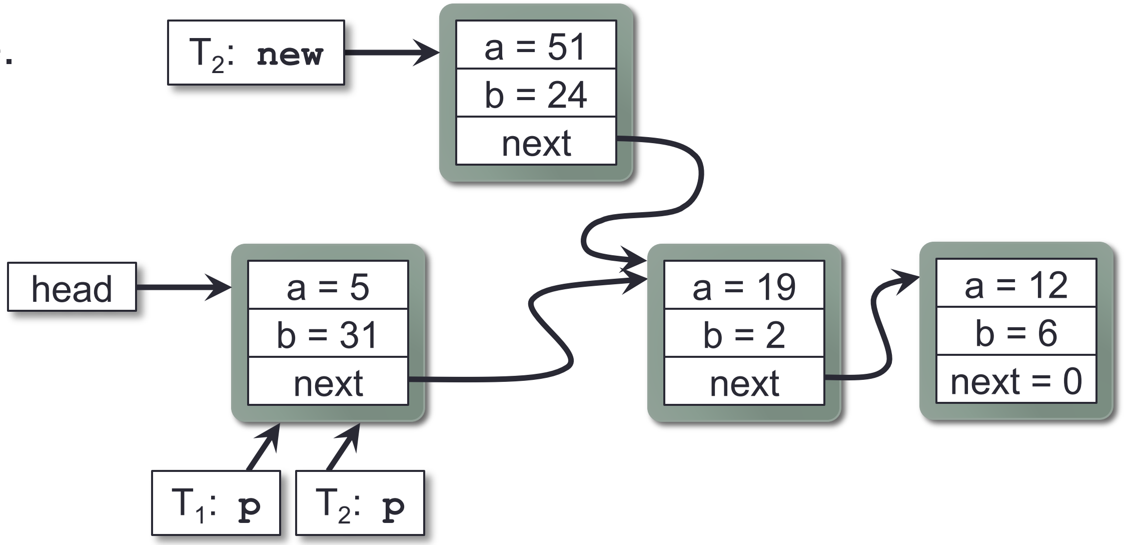


Order of Operations

- **What if we could impose a more intelligent ordering?**
- When T_2 inserts a node:
  - Step 1: Prepare the new node, but don't insert it into the list yet

```
list_node *new = malloc(sizeof(list_node));
new->a = 51;
new->b = 24;
new->next = p->next;
```

    - Last three operations can occur in any order.
      No one cares, because they aren't visible to anyone.
- T_1 can go merrily along;
  T_2 hasn't made any visible changes yet.

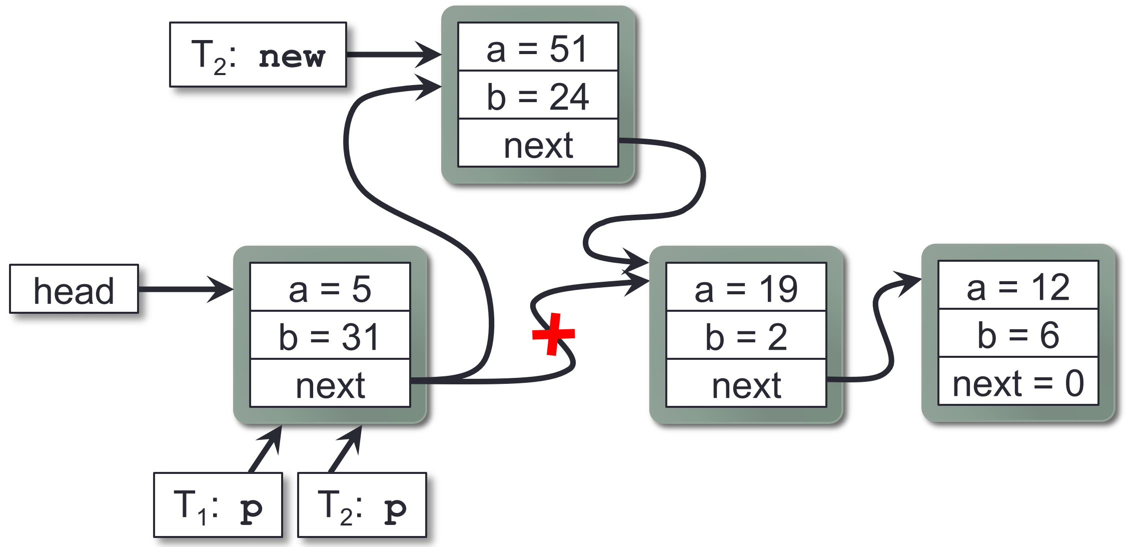


Order of Operations (2)

- **What if we could impose a more intelligent ordering?**
- When T_2 inserts a node:
  - Step 2: Atomically change the list to include the new node

    ```
    p->next = new;
    ```

    - **This is a single-word write.** If the CPU can perform this atomically, then threads will either see the old version of the list, or the new version.
- **Result: Reader threads will never see an invalid version of the list**
  - For this to work, we must ensure these operations happen in the correct order



Read-Copy-Update

- This mechanism is called **Read-Copy-Update** (RCU)
  - A lock-free mechanism for providing a kind of mutual exclusion
- All changes to shared data structures are made in such a way that concurrent readers never see intermediate state
  - They either see the old version of the structure, or they see the new version.
- Changes are broken into two phases:
  - If necessary, a copy is made of specific parts of the data structure. Changes take place on the copy; readers cannot observe them.
  - Once changes are complete, they are made visible to readers in a single atomic operation.
- In RCU, this atomic operation is always changing a pointer from one value to another value
  - e.g. T_2 performs **`p->next = new`**, and change becomes visible

Publish and Subscribe

- It's helpful to think of changing the `p->next` pointer in terms of a publish/subscribe problem
- T_2 operations:
  - Step 1: Prepare the new node

```
list_node *new = malloc(sizeof(list_node));
new->a = 51;
new->b = 24;
new->next = p->next;
```

  - Step 2: Atomically change the list to include the new node

```
p->next = new;
```

- Before the new node is **published** for others to access, all initialization must be completed
- We can enforce this with a write memory barrier
  - Enforce that all writes before the barrier are completed before any writes after the barrier are started. (Note: also an optimization barrier for the compiler…)

Publish and Subscribe (2)

- Implement this as a macro:

```
/* Atomically publish a value v to pointer p.    */
/* smp_wmb() also includes optimization barrier. */
#define rcu_assign_pointer(p, v) ({ \
    smp_wmb(); (p) = (v); \
})
```

  - IA32 and x86-64 ISAs both guarantee that if the pointer-write is properly word-aligned (or dword-aligned), it will be atomic.
  - (Even on multiprocessor systems!)
- T_2 operations become:

```
list_node *new = malloc(sizeof(list_node));
new->a = 51;
new->b = 24;
new->next = p->next;
/* Publish the new node */
rcu_assign_pointer(p->next, new);
```

Publish and Subscribe (3)

- T_1 needs to see the "current state" of the **`p->next`** pointer (whatever that value might be when it reads it)
- Example: T_1 is looking for node with a specific value of **`a`**:

```
list_node *p = head;
int b = -1;
while (p != NULL) {
  if (p->a == value) {
    b = p->b;
    break;
  }
  p = p->next;
}
return b;
```

- When T_1 reads **`p->next`**, it is **subscribing** to most recently published value

Publish and Subscribe (4)

- Example: T_1 is looking for node with a specific value of **`a`**:

```
list_node *p = head;
int b = -1;
while (p != NULL) {
  if (p->a == value) {
    b = p->b;
    break;
  }
  p = p->next;
}
return b;
```

- Must ensure that the read of **`p->next`** is completed before any accesses to **`p->a`** or **`p->b`** occur
  - Could use a read memory barrier, but IA32 already ensures that this occurs automatically
  - (Not all CPUs ensure this, e.g. DEC ALPHA CPU)

Publish and Subscribe (5)

- Again, encapsulate this "subscribe" operation in a macro:

```
/* Atomically subscribe to a pointer p's value. */
#define rcu_dereference(p) ({ \
    typeof(p) _value = ACCESS_ONCE(p); \
    smp_read_barrier_depends(); \
    (_value);
})
```

- On IA32, **`smp_read_barrier_depends()`** is a no-op
  - On DEC ALPHA, it's an actual read barrier
- **`ACCESS_ONCE(x)`** is a macro that ensures **`p`** is read directly from memory, not a register
  - (Usually generates no additional instructions beyond a memory-read operation)
- Subscribing to a pointer is <u>very</u> inexpensive. Nice!

Publish and Subscribe (6)

- Updated version of T_1 code:

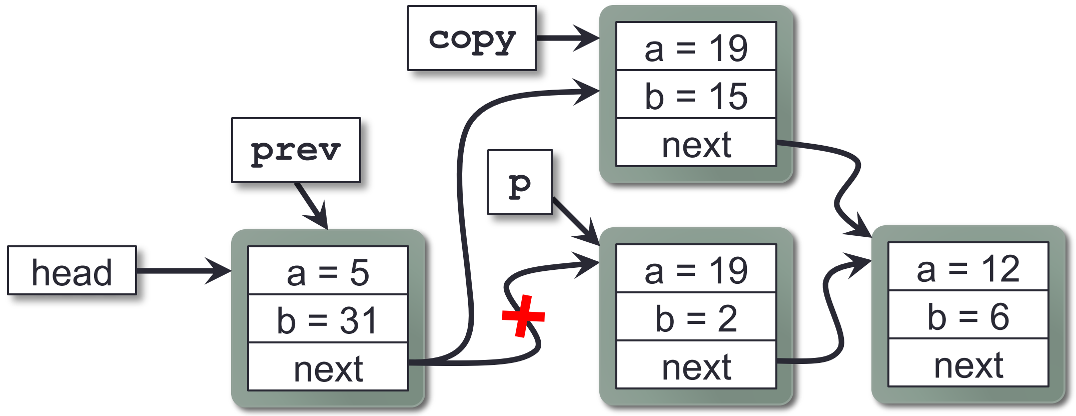
```
list_node *p = rcu_dereference(head);
int b = -1;
while (p != NULL) {
  if (p->a == value) {
    b = p->b;
    break;
  }
  p = rcu_dereference(p->next);
}
return b;
```

- So far, this is an extremely inexpensive mechanism
  - Writers must sometimes perform extra copying, and use a write memory barrier.
  - But, we expect writes to occur infrequently. And, writers don't block anyone anymore. (!!!)
  - Usually, readers incur zero overhead from RCU. (!!!)

Modifying a List Node

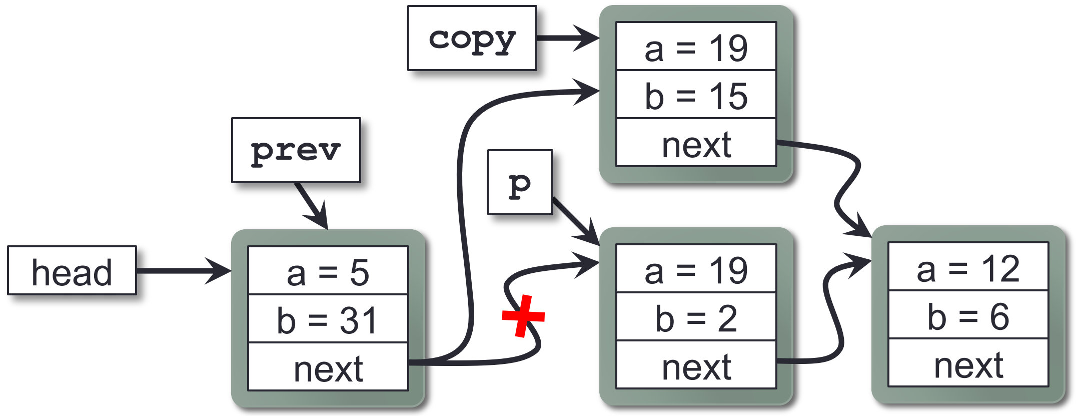
- Another example: change node with **`a`** = 19; set **`b`** = 15
  - Assume pointer to node being changed is in local variable **`p`**
  - Assume pointer to previous node is in **`prev`**
  - (Also, assume **`rcu_dereference()`** was used to navigate to **`p`**)
- Can't change the node in place; must make a copy of it

```
copy = malloc(sizeof(list_node));
copy->a = p->a;
copy->b = 15;
copy->next = p->next;
rcu_assign_pointer(prev->next, copy);
```



Modifying a List Node (2)

- Since **`rcu_assign_pointer()`** atomically publishes the change, readers must fall into one of two categories:
  - Readers that saw the old value of **`prev->next`**, and therefore end up at the old version of the node
  - Readers that see the new value of **`prev->next`**, and therefore end up at the new version of the node
- All readers will see a valid version of the shared list
  - And, we achieve this with much less overhead than with locking
  - (The writer has to work a bit harder…)



Modifying a List Node (3)

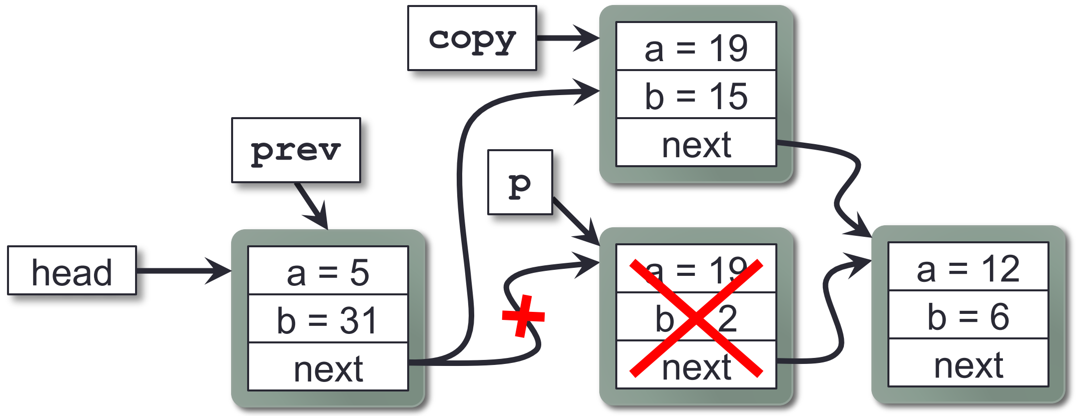
- Are we finished?

```
copy = malloc(sizeof(list_node));
copy->a = p->a;
copy->b = 15;
copy->next = p->next;
rcu_assign_pointer(prev->next, copy);
```

- Thread must deallocate the old node, or else there will be a memory leak

```
free(p);
```

- Problems?
  - If a reader saw the old version of **`prev->next`**, they may still be using the old node



Reclaiming Old Data

- The hardest problem in RCU is ensuring that old data is only deleted after all readers have finished with it
- **How do we tell that all readers have actually finished?**

- Define the concept of a **read-side critical section**:
  - A reader enters a read-side critical section when it reads an RCU pointer (**`rcu_dereference()`**)
  - A reader leaves the read-side critical section when it is no longer using the RCU pointer
- Require that readers explicitly denote the start and end of read-side critical sections in their code:
  - **`rcu_read_lock()`** starts a read-side critical section
  - **`rcu_read_unlock()`** ends a read-side critical section

Read-Side Critical Sections

- Update T_1 to declare its read-side critical section:

```
rcu_read_lock();     /* Enter read-side critical section */
list_node *p = rcu_dereference(head);
int b = -1;
while (p != NULL) {
  if (p->a == value) {
    b = p->b;
    break;
  }
  p = rcu_dereference(p->next);
}
rcu_read_unlock();  /* Leave read-side critical section */
return b;
```

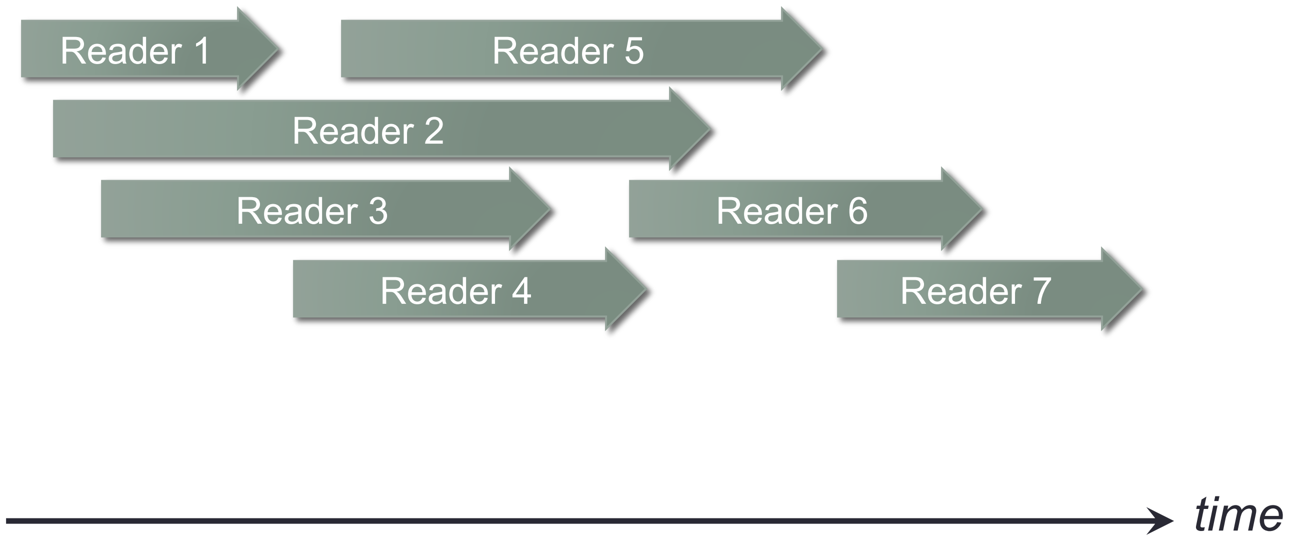
Read-Side Critical Sections (2)

- A critical constraint on read-side critical sections:
  - **Readers <u>cannot</u> block / sleep inside read-side critical sections!**
  - No yielding the CPU, long running IO operations, or blocking calls
- Should be obvious that T_1 follows this constraint:

```
rcu_read_lock();  /* Start read-side critical section */
list_node *p = rcu_dereference(head);
int b = -1;
while (p != NULL) {
  if (p->a == value) {
    b = p->b;
    break;
  }
  p = rcu_dereference(p->next);
}
rcu_read_unlock();  /* End read-side critical section */
return b;
```

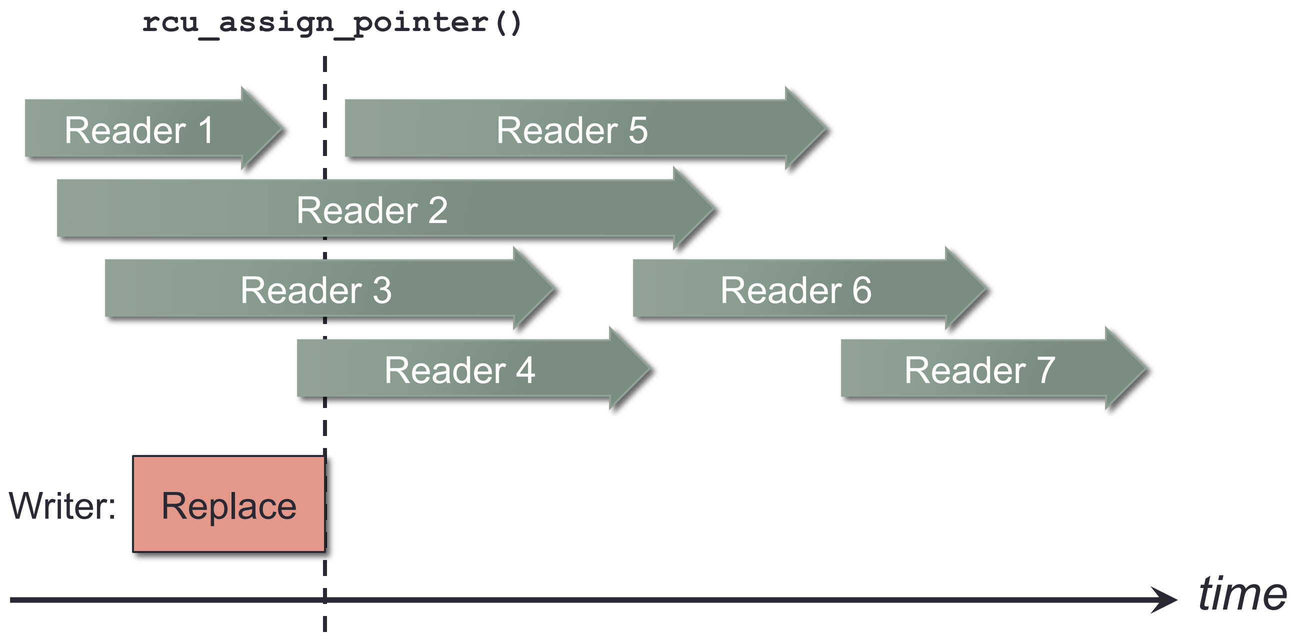
Read-Side Critical Sections (3)

- Can use read-side critical sections to define when old data may be reclaimed
- Each reader’s interaction with shared data structure is contained entirely within its read-side critical section
  - Each reader’s arrow starts with a call to **`rcu_read_lock()`**, and ends with **`rcu_read_unlock()`**



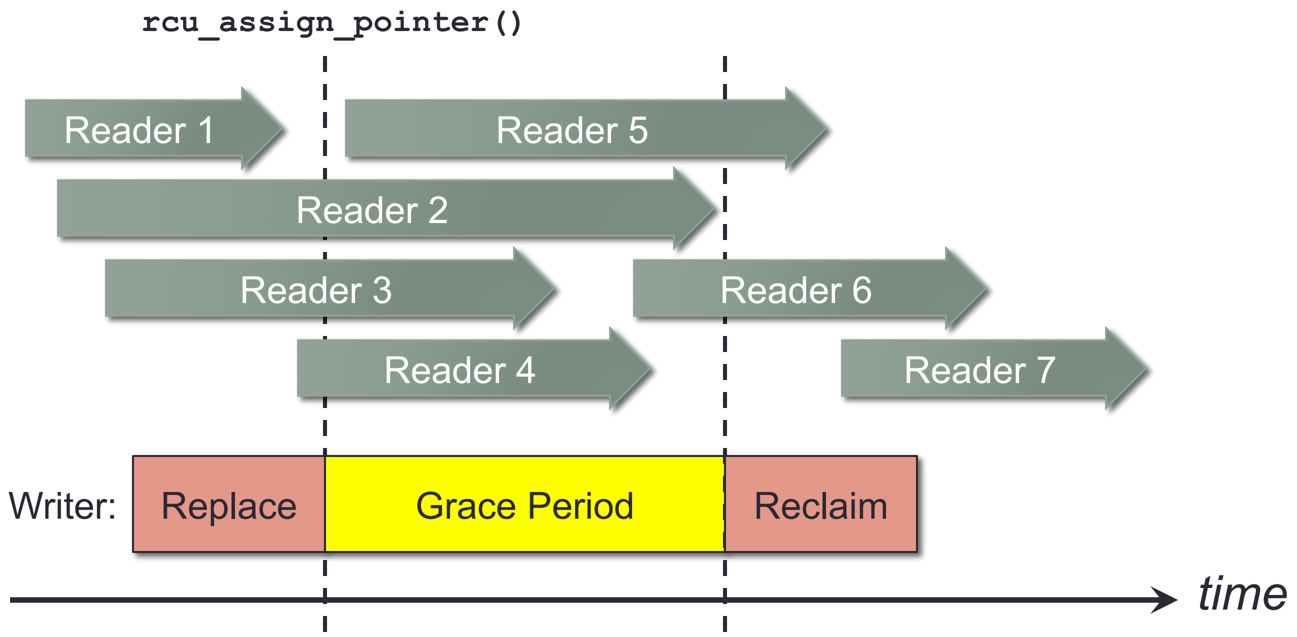
Read-Side Critical Sections (4)

- Writer publishes a change to the data structure with a call to **`rcu_assign_pointer()`**
  - Divides readers into two groups – readers that might see the old version, and readers that cannot see the old version
- What readers might see the old version of the data?
  - Any reader that called **`rcu_read_lock()`** before **`rcu_assign_pointer`** is called



Read-Side Critical Sections (5)

- **When can the writer reclaim the old version of the data?**
- After all readers that called **`rcu_read_lock()`** before **`rcu_assign_pointer()`** have also called **`rcu_read_unlock()`**
- This is the earliest that the writer may reclaim the old data; it is also allowed to wait longer (this imposes no cost except that resources are still held)
- Time between release and reclamation is called the **grace period**



End of Grace Period

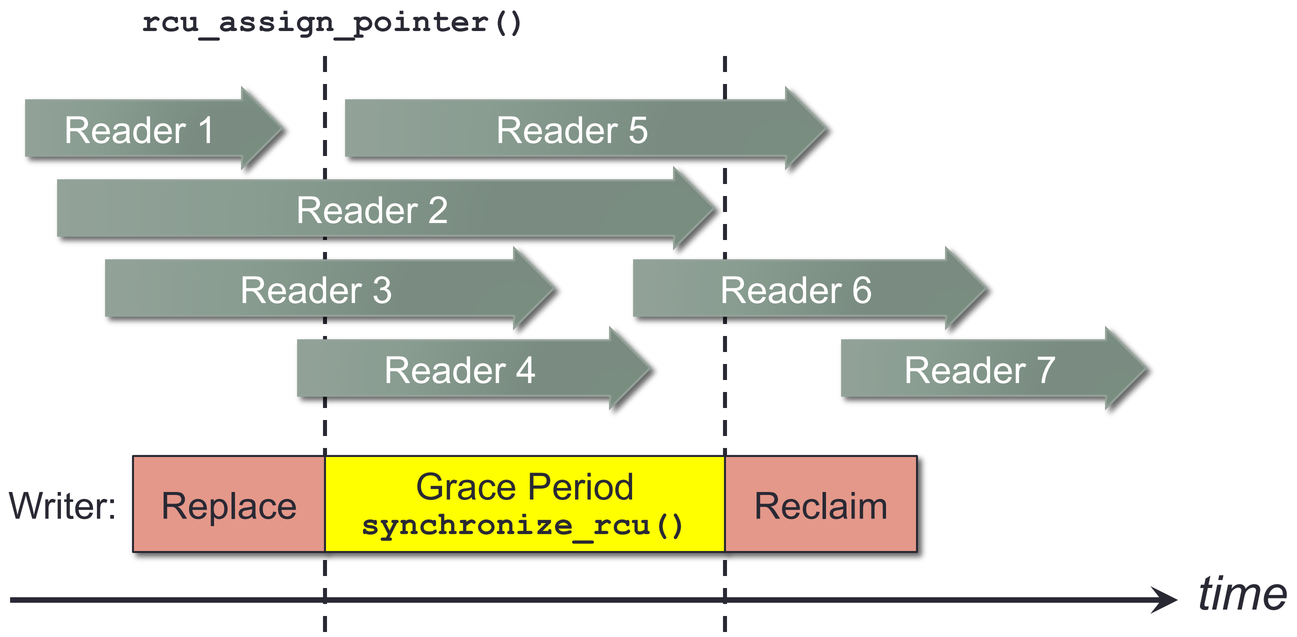
- Writer must somehow find out when the grace period is over
    - Doesn’t have to be a precise determination; can be approximate, as long as writer can’t think it’s over before it’s actually over
- Encapsulate this in the **`synchronize_rcu()`** operation
    - This call blocks the writer until the grace period is over
- Updating our writer’s code:

```
copy = malloc(sizeof(list_node));
copy->a = p->a;
copy->b = 15;
copy->next = p->next;
rcu_assign_pointer(prev->next, copy);

/* Wait for readers to get out of our way... */
synchronize_rcu();
free(p);
```

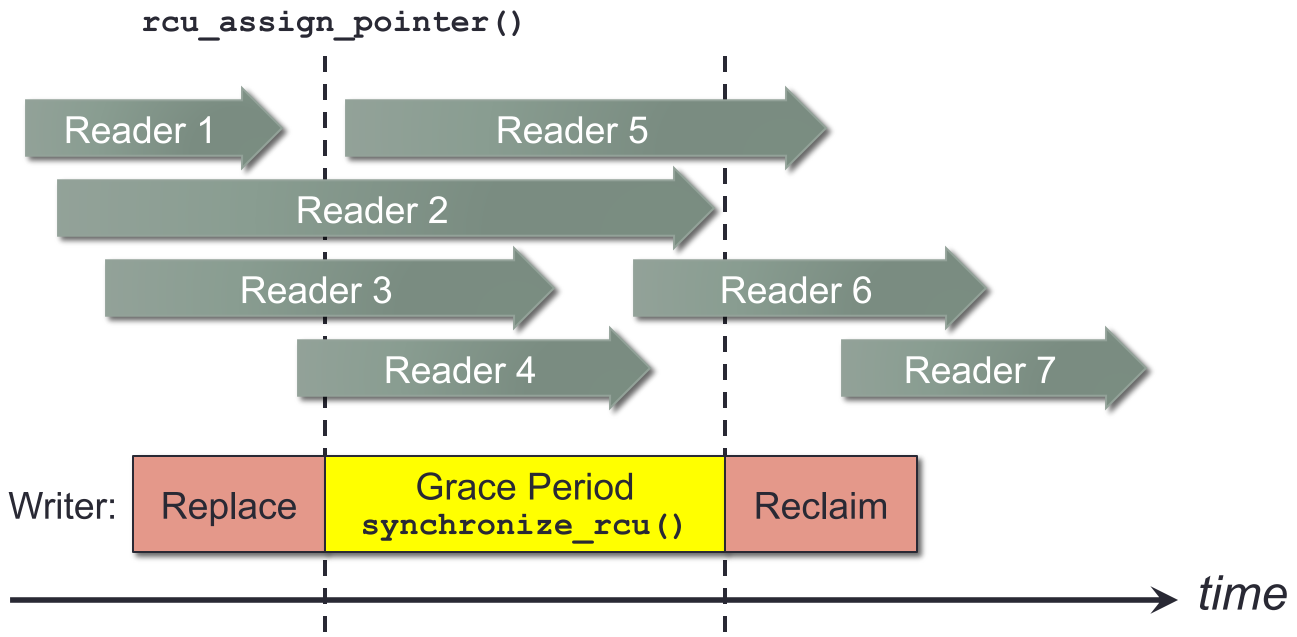
End of Grace Period (2)

- Updated diagram with call to `synchronize_rcu()`
- **But how does this actually work?**



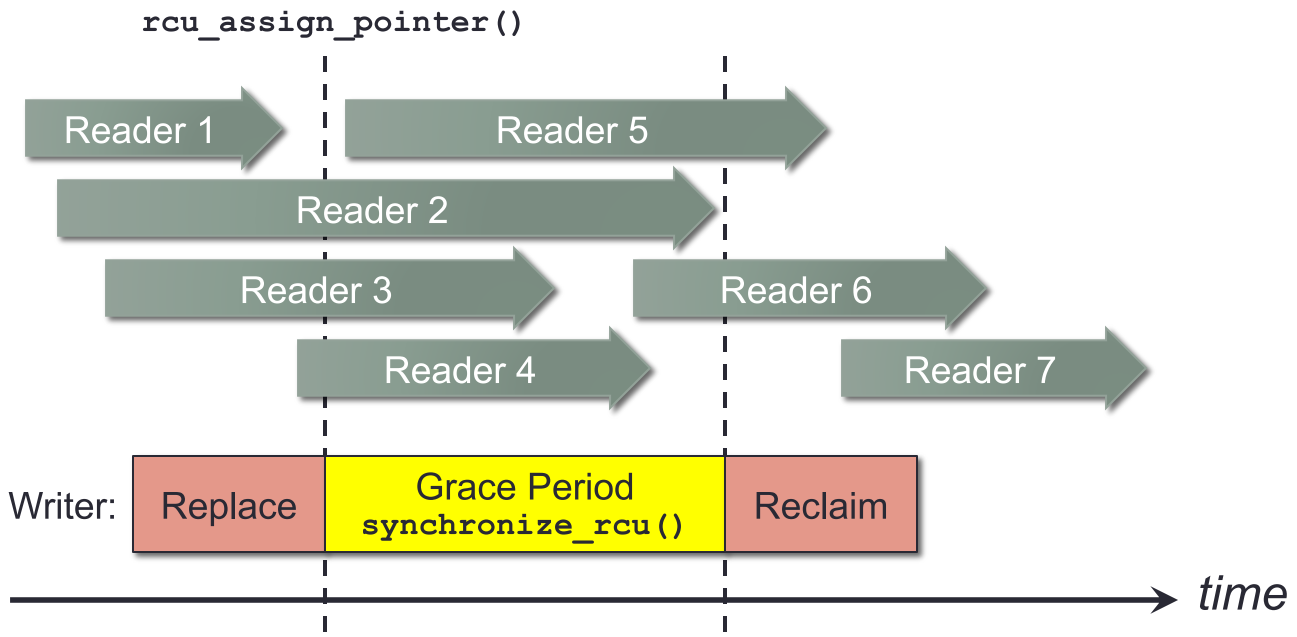
End of Grace Period (3)

- Recall: readers are not allowed to block or sleep when inside a read-side critical section
- What is the maximum number of readers that can actually be inside read-side critical sections at any given time?
  - Same as the number of CPUs in the system
  - If a reader is inside its read-side critical section, it must also occupy a CPU



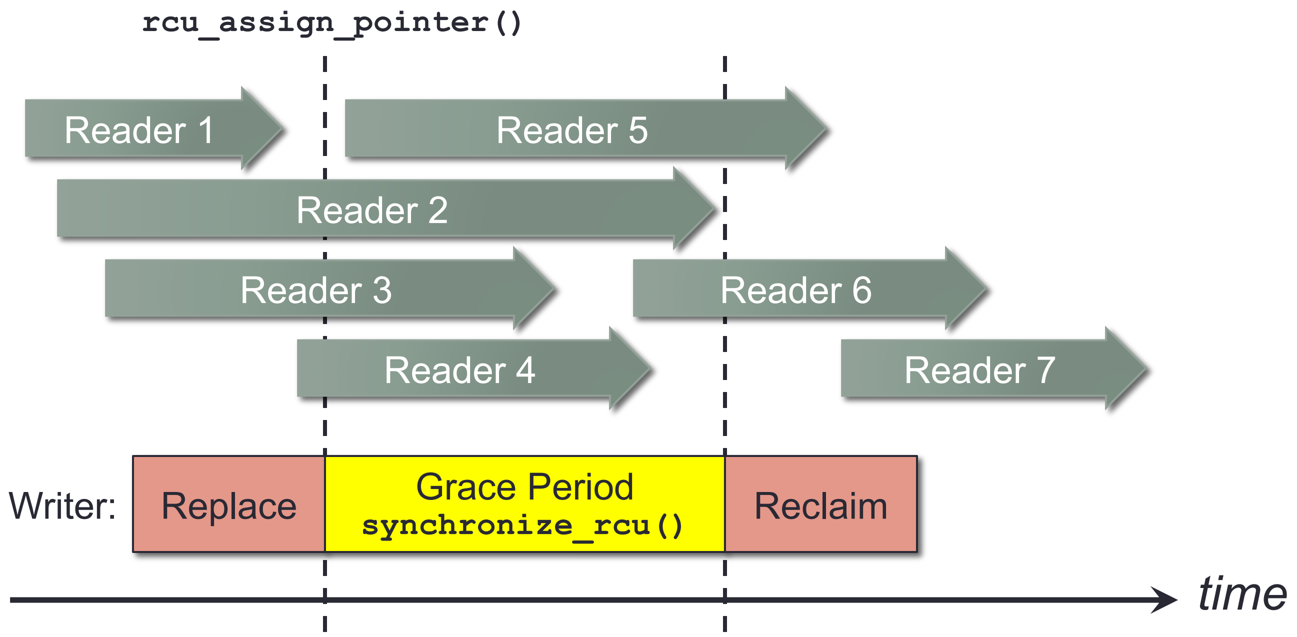
End of Grace Period (4)

- Recall: readers are not allowed to block or sleep when inside a read-side critical section
- Also, require that the operating system <u>cannot</u> preempt a kernel thread that's currently inside a read-side critical section
  - Don't allow OS to context-switch away from a thread in a read-side critical section
  - In other words, don't allow kernel preemption during the read-side critical section



End of Grace Period (5)

- Recall: readers are not allowed to block or sleep when inside a read-side critical section
- If a CPU executes a context-switch, then we know that kernel-thread already completed any read-side critical section it might have been in…
- Therefore, **`synchronize_rcu()`** can simply wait until at least one context-switch has occurred on every CPU in the system
  - Gives us an upper bound on the length of the grace period… Good enough! ☺



Completing the RCU Implementation

- Now we know enough to complete RCU implementation
- **`synchronize_rcu()`** waits until at least one context-switch has occurred on each CPU

```
void synchronize_rcu() {
  int cpu;
  for_each_online_cpu(cpu)
    run_on(cpu);
}
```

  - **`run_on()`** causes the kernel thread to run on a specific processor
  - Can be implemented by setting kernel thread's processor-affinity, then yielding the CPU
  - Once the kernel thread has switched to every processor, at least one context-switch has definitely occurred on every CPU (duh!)

Completing the RCU Implementation (2)

- On a single-processor system, **`synchronize_rcu()`** is a no-op (!!!)
  - **`synchronize_rcu()`** might block; therefore it cannot be called from within a read-side critical section
  - Any read-side critical section started before **`synchronize_rcu()`** was called, must have already ended at this point
  - Therefore, since **`synchronize_rcu()`** is running on the CPU, the grace period is already over, and the old data may be reclaimed

Completing the RCU Implementation (3)

- **`read_lock()`** and **`read_unlock()`** are very simple:
  - Since **`synchronize_cpu()`** uses context-switches to tell when grace period is over, these functions don't actually have to do any bookkeeping (!!!)
- On a multicore system, or an OS with kernel preemption:
  - Must enforce constraint that readers cannot be switched away from while inside their read-side critical section

```
void read_lock() {
  preempt_disable(); /* Disable preemption  */
}
void read_unlock() {
  preempt_enable();  /* Reenable preemption */
}
```

  - (**`preempt_disable()`** and **`preempt_enable()`** simply increment or decrement **`preempt_count`**; see Lecture 8)

Completing the RCU Implementation (4)

- On a single-processor system with OS that doesn't allow kernel preemption:
  - (Recall: this means all context-switches will be **scheduled context-switches**)
- In this case, **`read_lock()`** and **`read_unlock()`** don't have to do anything
  - Already have a guarantee that nothing can cause a context-switch away from the kernel thread inside its read-side critical section

- The "implementation" also becomes a no-op:

```
#define read_lock()
#define read_unlock()
```

Results: The Good

- RCU is a very sophisticated mechanism for supporting concurrent access to shared data structures
  - Conceptually straightforward to understand how to implement readers and writers
  - Understanding how it works is significantly more involved…
- Doesn’t involve any locks:
  - Little to no lock overhead, no potential for deadlocks, no priority-inversion issues with priority scheduling
- Extremely lightweight
  - On most platforms, many RCU operations either reduce to a single instruction, or a no-op
  - Only requires a very small number of clocks; <u>far</u> fewer than acquiring a lock

Entire RCU Implementation

```
/** RCU READER SUPPORT FUNCTIONS **/

/* Enter read-side critical section */
void read_lock(void) {
  preempt_disable();
}

/* Leave read-side critical section */
void read_unlock(void) {
  preempt_enable();
}

/* Subscribe to pointer p's value */
/* smp_wmb() includes opt.barrier */
#define rcu_dereference(p) ({ \
  typeof(p) _v = ACCESS_ONCE(p); \
  smp_read_barrier_depends(); \
  (_value); })
```

```
/** RCU WRITER SUPPORT FUNCTIONS **/

/* Publish a value v to pointer p */
/* smp_wmb() includes opt.barrier */
#define rcu_assign_pointer(p, v) \
 ({ smp_wmb(); (p) = (v); })

/* Wait for grace period to end */
void synchronize_rcu(void) {
  int cpu;
  for_each_online_cpu(cpu)
    run_on(cpu);
}
```

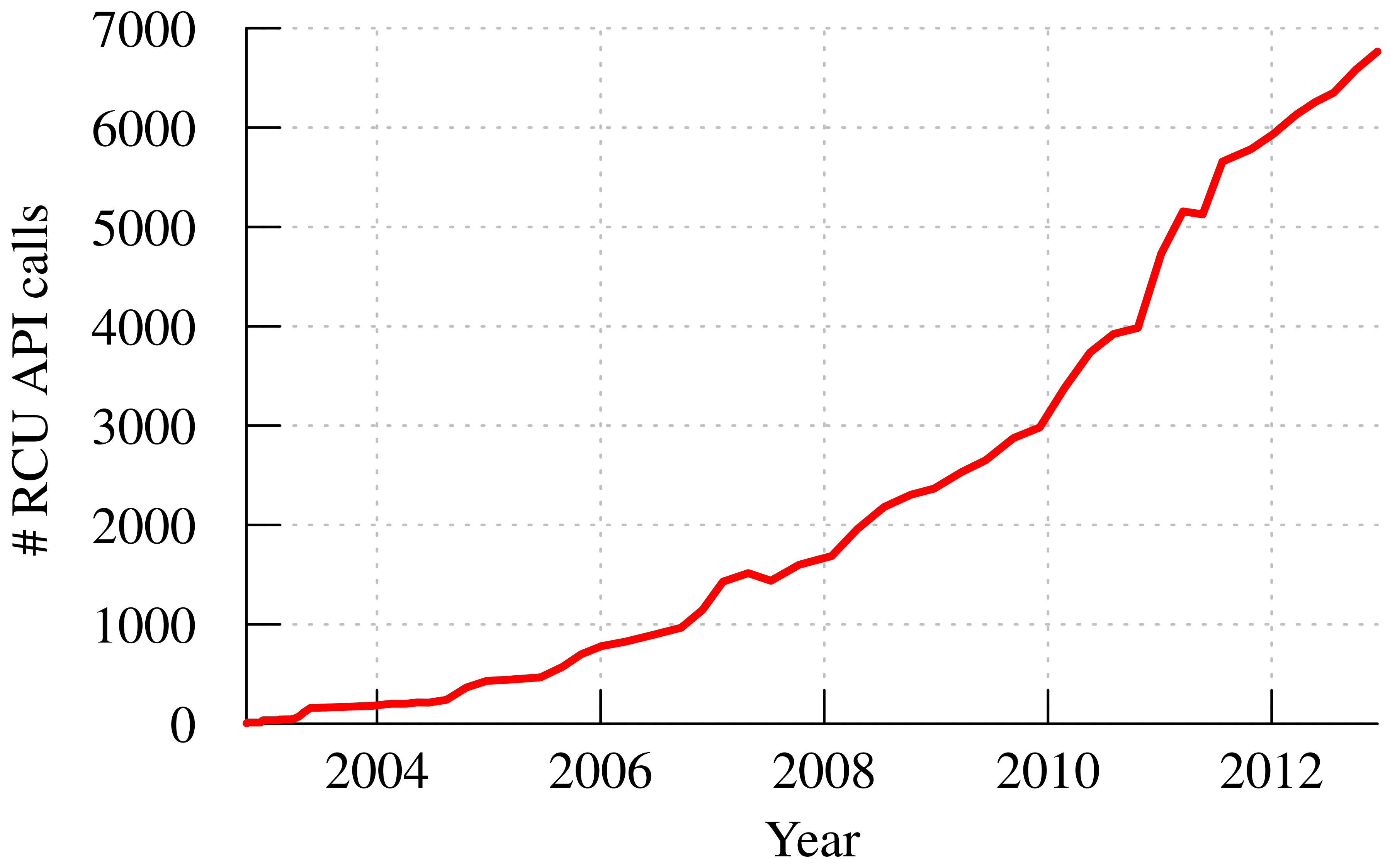
Results: The Bad and the Ugly

- RCU is only useful in very specific circumstances:

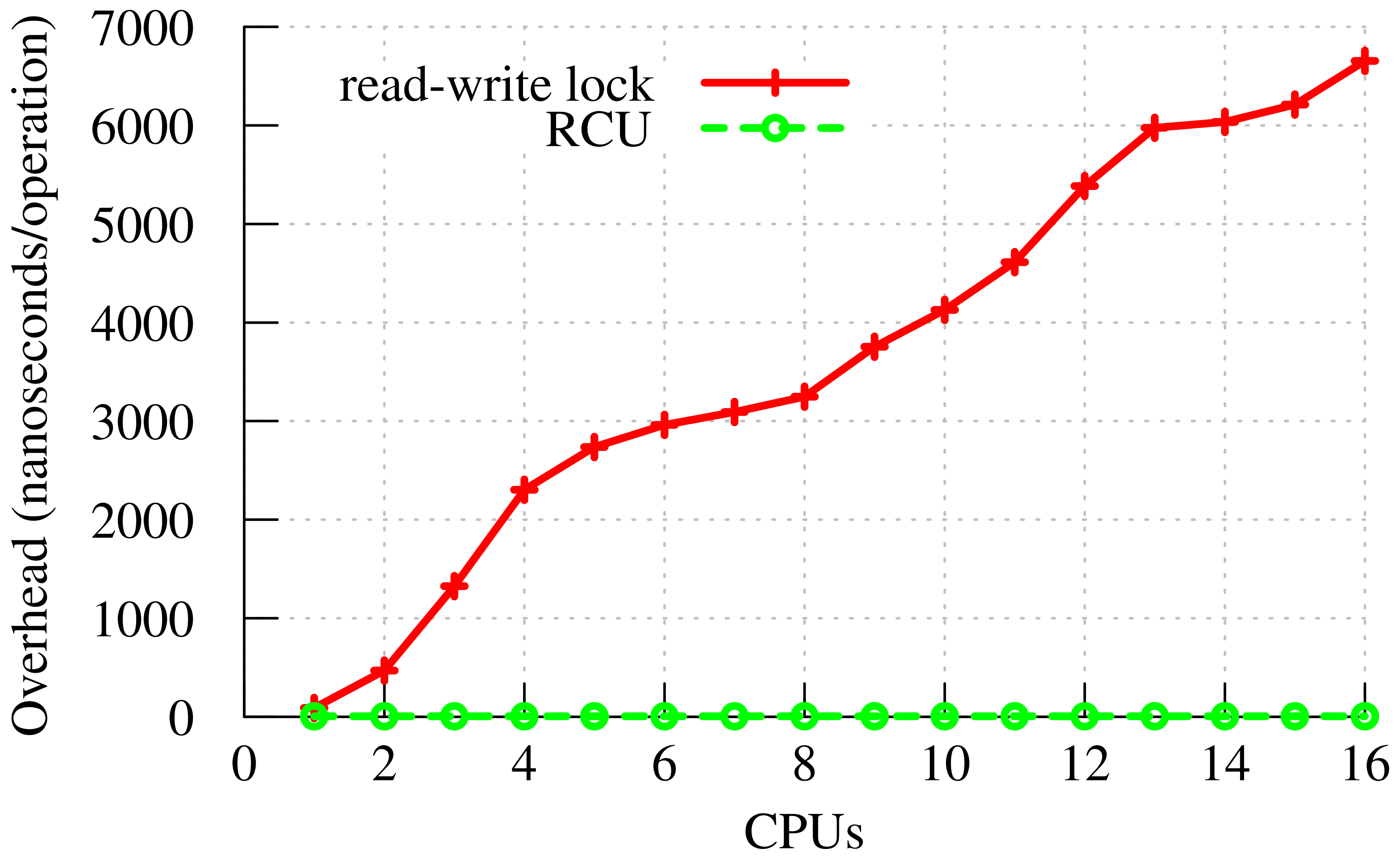
- Must have <u>many</u> more readers than writers
- Consistency <u>must not</u> be a strong requirement
  - Under RCU, readers may see a mix of old and new versions of data, or even only old data that is about to be reclaimed

- If either of these conditions isn't met, may be much better to rely on more standard lock-based approaches
- Surprisingly, many parts of Linux satisfy the above circumstances, and RCU is becoming widely utilized

RCU Use in Linux Kernel over Time



RCU vs. Read/Write Lock Overhead



RCU Implementation Notes

- There are much more advanced implementations of RCU
- RCU discussed today is known as “Classic RCU”
  - Many refinements to the implementation as well, offering additional features, and improving performance and efficiency
  - Our implementation is a “toy implementation,” but it still works
  - (Also doesn’t support multiple writers accessing the same pointer; need to use locks to prevent this, so it gets much slower…)
- SRCU (Sleepable RCU) allows readers to sleep inside their read-side critical sections
  - Also allows preemption of kernel threads inside read-side critical sections
- Preemptible RCU also supports readers suspending within their read-side critical sections

References

- For everything you could ever want to know about RCU:
  - Paul McKenney did his PhD research on RCU, and has links to an extensive array of articles, papers and projects on the subject
  - http://www2.rdrop.com/users/paulmck/RCU/
- Most helpful/accessible resources:
  - What is RCU, Really? (3-part series of articles)
    - http://www.rdrop.com/users/paulmck/RCU/whatisRCU.html
  - What Is RCU? (PDF of lecture slides)
    - http://www.rdrop.com/~paulmck/RCU/RCU.Cambridge.2013.11.01a.pdf
  - User-Level Implementations of Read-Copy Update
    - http://www.rdrop.com/users/paulmck/RCU/urcu-main-accepted.2011.08.30a.pdf (actual article)
    - http://www.rdrop.com/users/paulmck/RCU/urcu-supp-accepted.2011.08.30a.pdf (supplemental materials)

References (2)

- Andrei Alexandrescu has also written a few good articles:
  - Lock-Free Data Structures (big overlap with many RCU concepts)
    - https://www.drdobbs.com/lock-free-data-structures/184401865
  - Lock-Free Data Structures with Hazard Pointers
    - https://www.drdobbs.com/lock-free-data-structures-with-hazard-po/184401890

- C++ Concurrency in Action, 2nd ed. by Anthony Williams
  - Another great discussion of lock-free data structures, API design for concurrency, etc.