ECE 454
Computer Systems Programming

Avoiding Locks

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Overview

- Challenges with Locking
- Non-Blocking Synchronization
- Read-Copy Update

Challenges with Locking

Locking: A Necessary Evil?

- Locks - easy solution to critical section problem
  - Protect shared data from corruption due to simultaneous updates
  - Protect against inconsistent views of intermediate states
- But locks have lots of problems
  - 1. Deadlock
  - 2. Priority inversion
  - 3. Not fault tolerant
  - 4. Convoying
  - 5. Expensive, even when uncontended
- Not easy to use correctly!

1. Deadlock

1. Deadlock

- Textbook definition: Set of threads blocked waiting for event that can only be caused by another thread in the same set

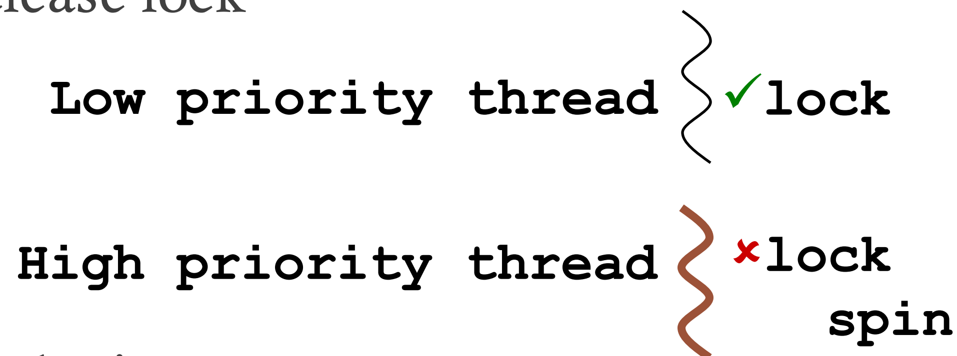
```
/* a threaded program with
   a potential for deadlock */

Thread1(){                  Thread2(){
   lock(a);                    lock(b);
   lock(b);                    lock(a);
   do_work();                  do_work();
   unlock(b);                  unlock(a);
   unlock(a);                  unlock(b);
}                           }
```

- Solutions exists but add complexity
  - E.g., specify lock order

2. Priority Inversion

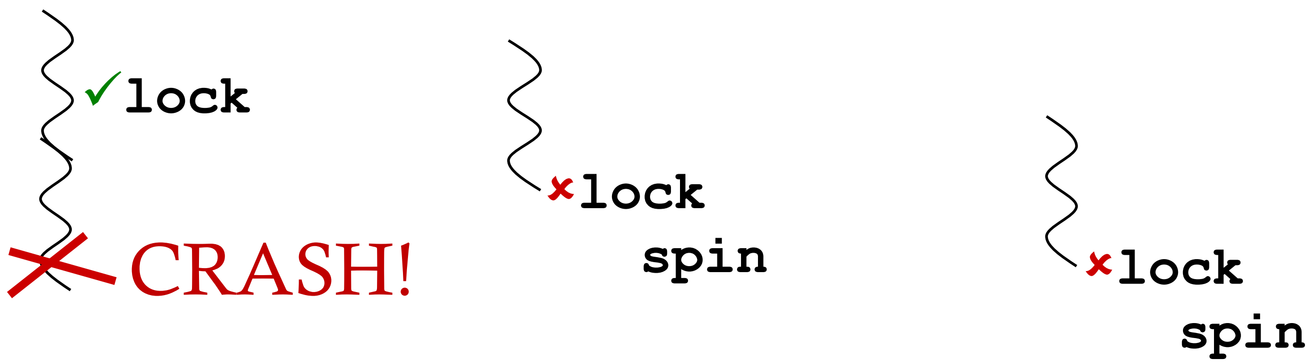
- Lower priority thread gets spinlock
- Higher priority thread becomes runnable and preempts it
  - Needs lock, starts spinning
  - Lock holder can't run and release lock



- Solutions exist but add complexity
  - E.g. disable preemption while holding spinlock, implement priority inheritance, etc.

3. Not Fault Tolerant

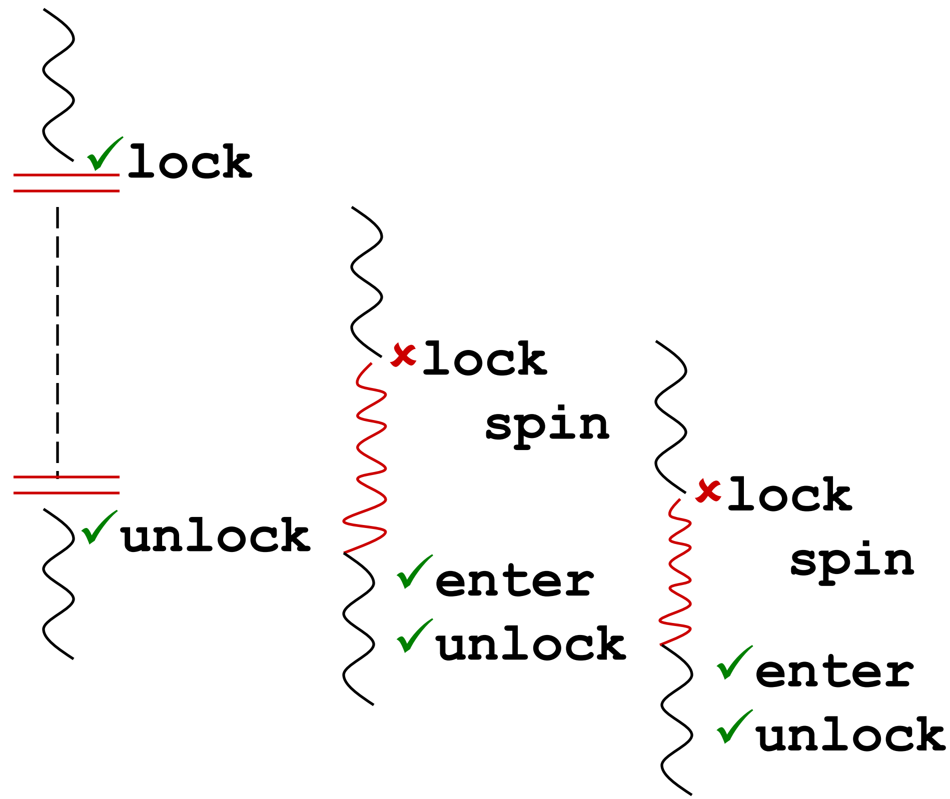
- If lock holder crashes, or gets delayed, no one makes progress



- Delays can happen due to preemption, page faults
  - Disable such delays, e.g., pin pages in memory
  - Avoid critical sections when delays will happen
- Crashes require abort / restart

4. Convoying

- Threads started at different times occasionally access shared data
- Expect shared data accesses to be spread out over time
  - Lock contention should be low
- Delay of lock holder allows other threads to catch up
  - Lock becomes contended and tends to stay that way
  - => Convoying



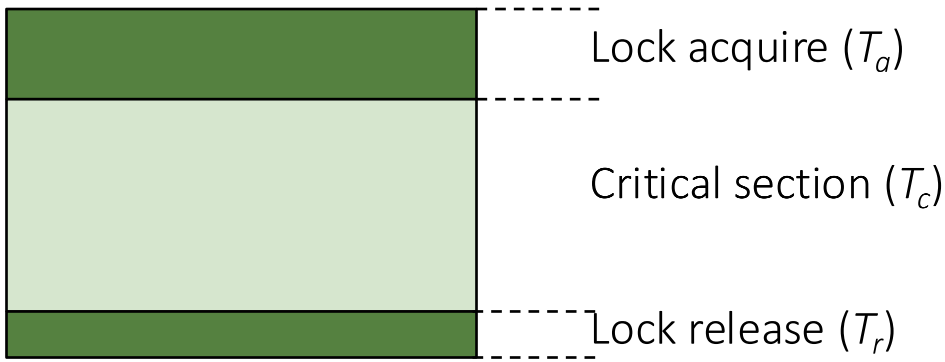
5. Expensive, Even When Uncontended!

Operation	Nanoseconds
Instruction	0.24
Clock Cycle	0.69
Atomic Increment	42.09
Cmpxchg Blind Cache Transfer	56.80
Cmpxchg Cache Transfer and Invalidate	59.10
SMP Memory Barrier (eieio)	75.53
Full Memory Barrier (sync)	92.16
CPU-Local Lock	243.10

McKenney, 2005 – 8-CPU 1.45 GHz PPC

Critical Section Efficiency

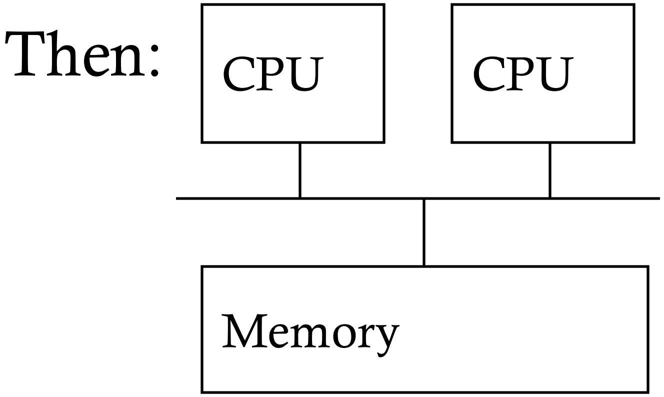
- Assuming little to no contention, and no caching effects in CS

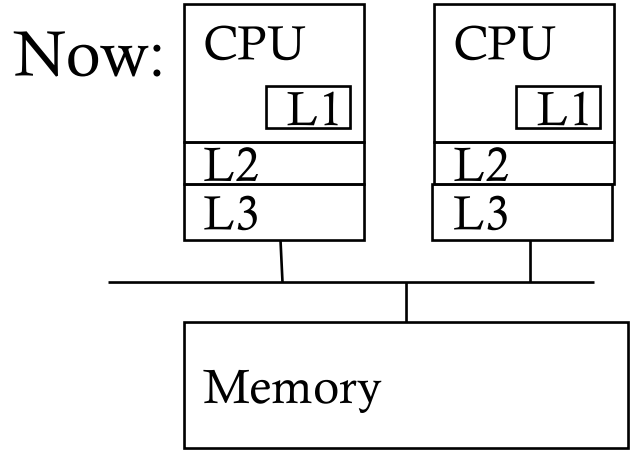


$$\text{Efficiency} = \frac{T_c}{T_c + T_a + T_r}$$

- Ta and Tr can take 100+ cycles, even with no contention
- Critical section efficiency must be addressed!

Causes: Deeper Memory Hierarchy



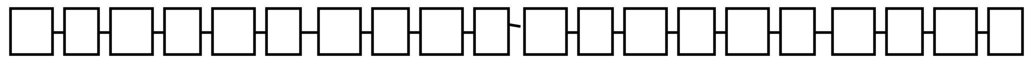


- Memory speeds have not kept up with CPU speeds
  - 1984: no caches needed, since instructions slower than memory accesses
  - after ~2005: 3-4 level cache hierarchies, since instruction speeds are orders of magnitude faster than memory accesses
- Synchronization ops typically execute at memory speed

Causes: Deeper Pipelines

Then:

Now:



- 1984: Many cycles per instruction
- 2005: Many instructions per cycle
  - 20 stage pipelines
  - CPU logic executes instructions out-of-order to keep pipeline full
  - Synchronization instructions cannot be reordered
  - => Synchronization stalls the pipeline

Performance

- Main issue with lock performance used to be contention
  - Techniques were developed to reduce overheads in contended case
    - E.g., MCS locks
- Today, issue is degraded performance even when locks are always available
  - Together with other concerns about locks

Locks: A Necessary Evil?

Idea: Don't lock if we don't need to!

- Use "lockless" synchronization
  - Design data structures so that locks are not required

Non-Blocking Synchronization

Non-Blocking Synchronization (NBS) Basics

- Think of NBS as a "lockless" synchronization scheme
  - With locking, threads access shared object under mutual exclusion
  - With NBS, threads can access shared object concurrently

- Idea: make change optimistically, if conflict detected, roll back

```
// atomically increment *counter using CAS
atomic_inc(int *counter) {
    int value;
    do {
        value = *counter;    // save value of counter
    } while (!CAS(counter, value, value+1);
}
```

- Complex updates (e.g. modifying multiple values in a structure) are hidden behind a single commit point using atomic instructions

Example: Lock-Based Stack

```
class Node {
  Node *next;
  int data;
};

Node *head; Lock *l;
```

```
void push(Node *node) {
  lock(l);
  node->next = head;
  head = node;
  unlock(l);
}
```

```
Node *pop() {
  int current = NULL;
  lock(l);
  if (head) {
    current = head;
    head = head->next;
  }
  unlock(l);
  return current;
}
```

Example: Lock-Free Stack

```
class Node {
  Node *next;
  int data;
};

Node *head;
```

```
void push(Node *node) {
  do {
    node->next = head;
  } while (!CAS(&head, node->next, node));
}
```

```
Node *pop() {
  Node *current = head;
  while (current) {
    if (CAS(&head, current, current->next)) {
      return current;
    }
    current = head; // head may have changed
  }
  return NULL;
}
```

Anything wrong?

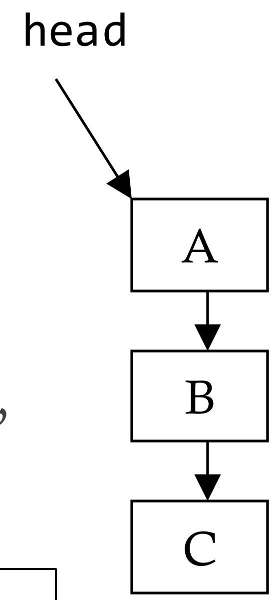
ABA Problem

- Notice that pop reads head twice
- If the value of head hasn't changed, then head is updated
- What if another thread updates head in between, does other work, and then changes head back to the old value?

```
Node *pop() {
  Node *current = head;
  while (current) {
    if (CAS(&head, current, current->next)) {
      return current;
    }
    …
}
```

ABA Problem

- Say Ti, Tj are both doing pops and pushes on this stack:
- Ti: starts `pop()`
  - `head is A`
  - `current is A`
  - `current->next is B (loaded in reg)`
  - Ti interrupted before it performs: `CAS(&head, current, current->next)`, i.e., before `head is assigned to B`

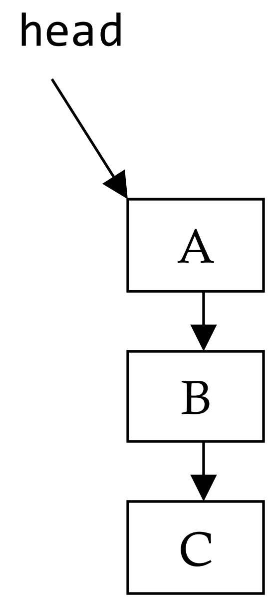



```
Node *current = head;
…
if (CAS(&head, current, current->next))
```

Ti is interrupted

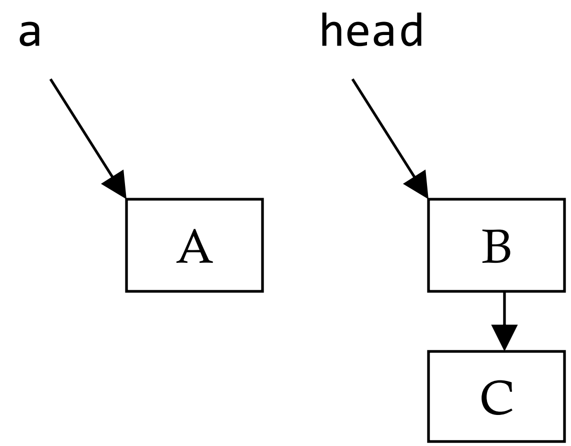
ABA Problem

- Say Ti, Tj are both doing pops and pushes on this stack:



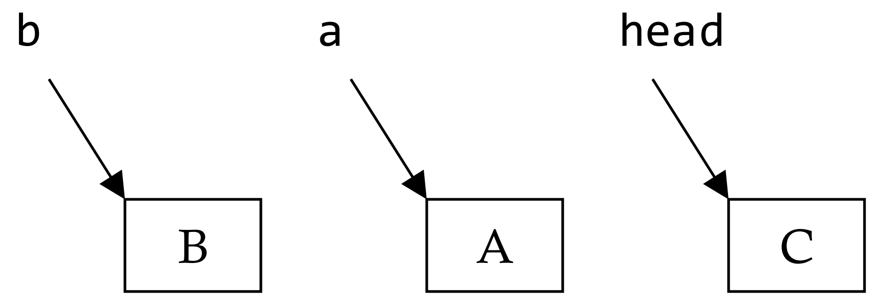
ABA Problem

- Say Ti, Tj are both doing pops and pushes on this stack:
- Tj:
  - `a=pop()`



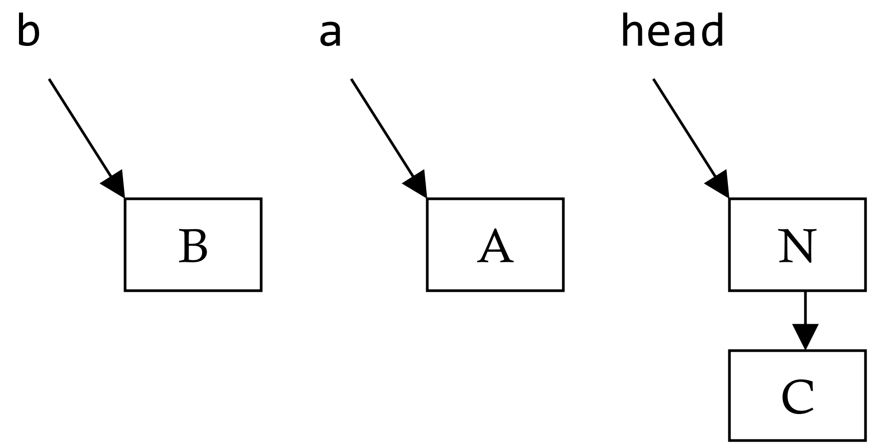
ABA Problem

- Say Ti, Tj are both doing pops and pushes on this stack:
- Tj:
  - `a=pop()`
  - `b=pop()`



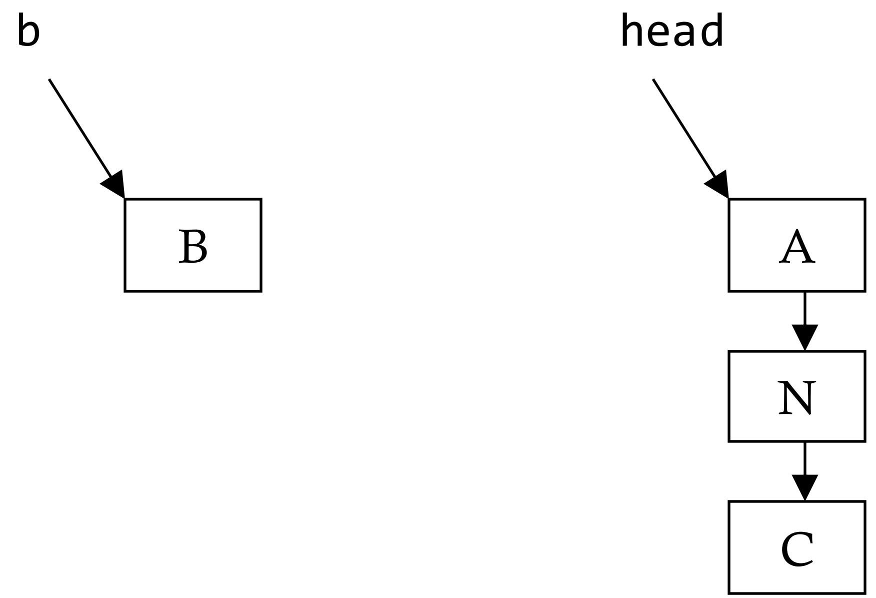
ABA Problem

- Say Ti, Tj are both doing pops and pushes on this stack:
- Tj:
  - `a=pop()`
  - `b=pop()`
  - `push(N)`



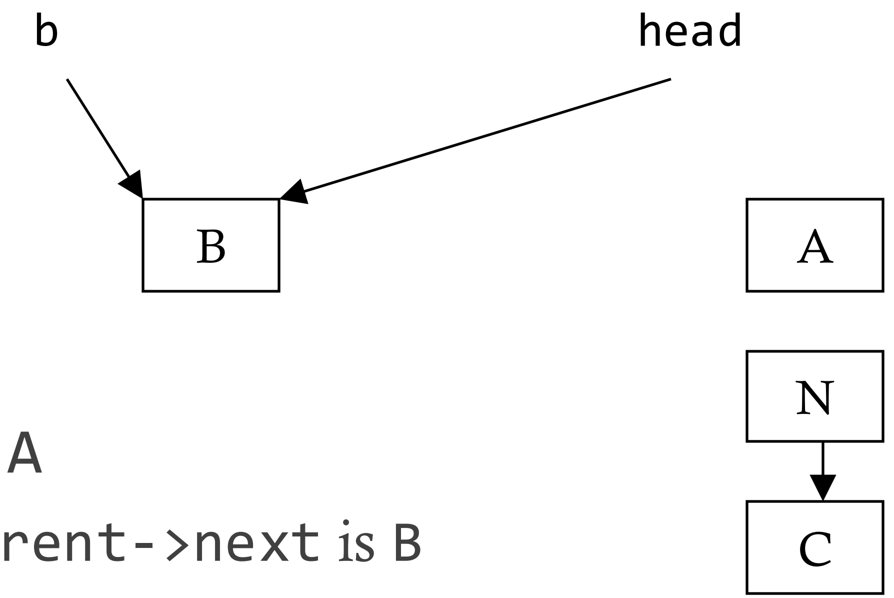
ABA Problem

- Say Ti, Tj are both doing pops and pushes on this stack:
- Tj:
  - `a=pop()`
  - `b=pop()`
  - `push(N)`
  - `push(a)`
    - ‘a’ is the same node that was returned by first `pop()`



ABA Problem

- Say Ti, Tj are both doing pops and pushes on this stack:
- Tj:
  - `a=pop()`
  - `b=pop()`
  - `push(N)`
  - `push(a)`



- Ti resumes: `head` is `A`
  - `current` is `A`, `current->next` is `B`
  - CAS succeeds, sets `head` to `B`!
  - Returns `A`, `A->next` set to `NULL`
  - Stack should have been `N, C`

One Solution

- Include a version number with every pointer
  - `pointer_t = <pointer, version>`
  - Increment version number every time pointed-to data is modified
  - Atomically update pointer and version using double-word CAS
    - Consider pop code: CAS(&head, current, current->next)
    - Say current = <A, 1>; After head is updated, head = <A, 2>
    - Version number ensures CAS will fail if data has changed
- Issues
  - Not every architecture provides double-word CAS operation
  - Old versions of pointers need to be freed
    - Use garbage collection to reclaim memory later
    - May restrict reuse of memory

Using NBS

- Generally used for simple, update-heavy data structures
  - E.g., linked list
  - See https://en.wikipedia.org/wiki/Non-blocking_linked_list
  - Hard to design data structures that use NBS

When do we need NBS Guarantees?

- When we need linearizability
  - Everyone agrees on all intermediate states
    - All updates appear instantaneous, occur in total order
    - Reads return value of last completed write
  - Imposes dependency between operations
    - Limits parallelism

- Do we always need linearizability?
  - Consider “top” program that lists all existing processes

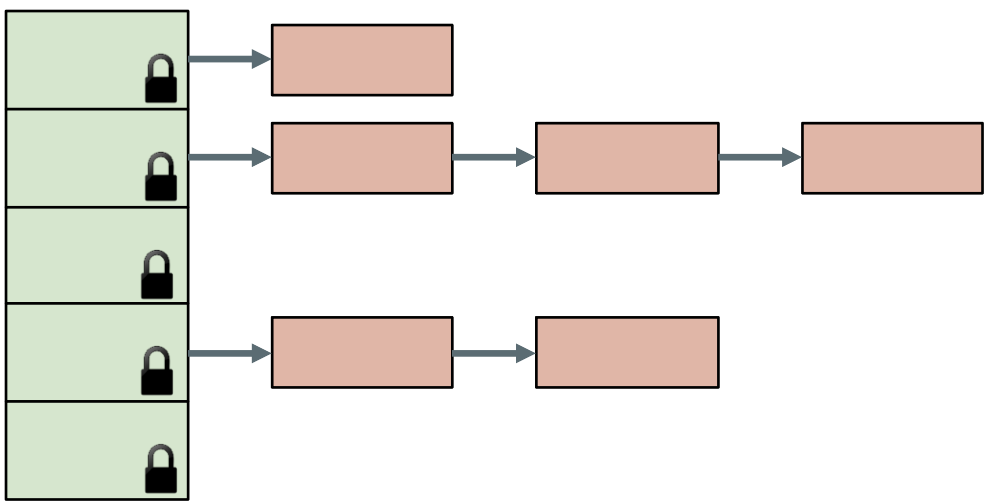
Read-Copy Update (RCU)

Read-Copy Update (RCU)

- What is RCU?
  - Paul McKenney's PhD thesis
  - A key part of the Linux scalability effort
- Reader-writer synchronization mechanism
  - Supports concurrency between multiple readers + single updater
  - Readers use no locks
    - Hence best for read-mostly data structures
  - Writers create new versions atomically
    - Either using atomic instructions or by locking out other writers
  - Readers may continue to access old versions
    - Old versions must be deleted at some point

Why RCU?

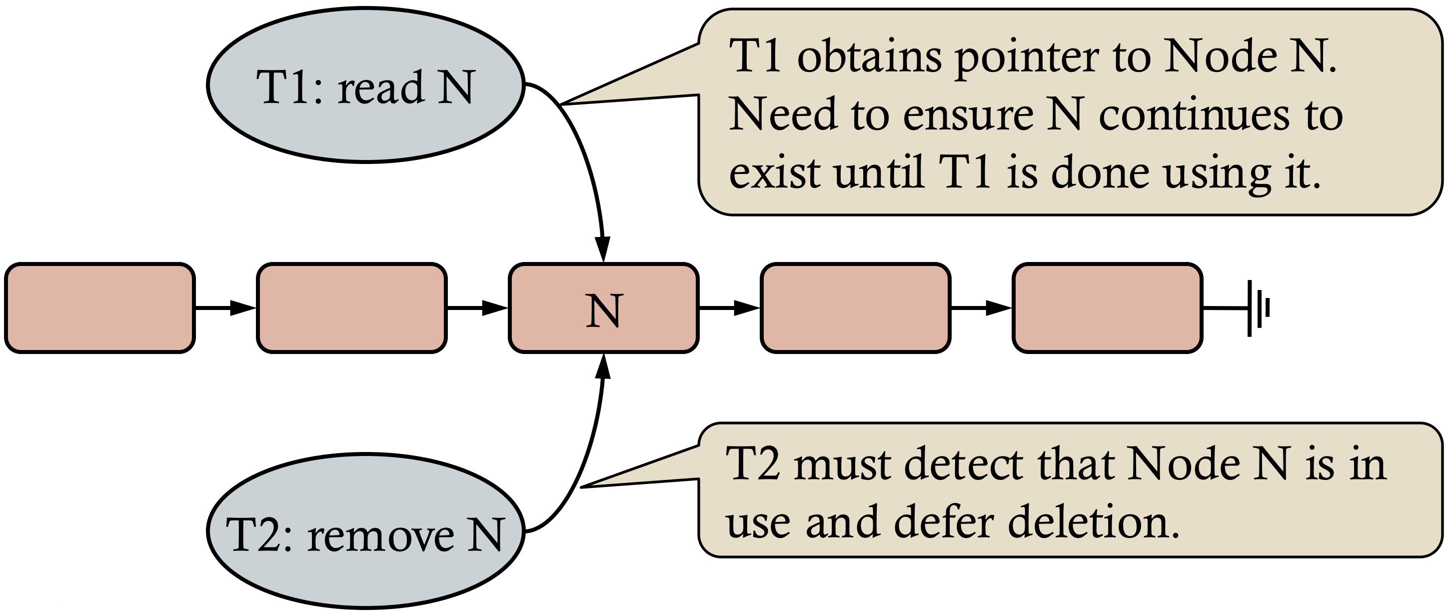
- Consider concurrent hash table example
  - Hash function selects bucket (entry in an array)
  - Collisions handled by chaining (linked list per bucket)
  - Use per-bucket locks to increase concurrency



- But recall costs of synchronization operations…

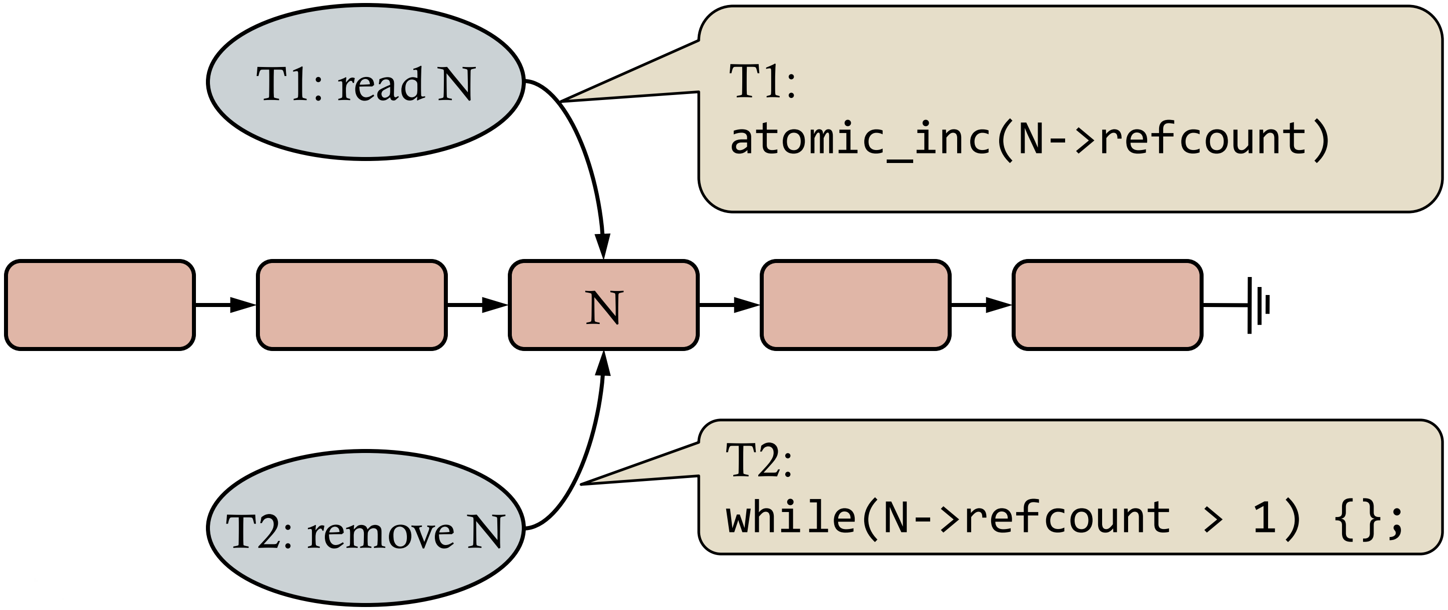
What about NBS?

- Non-blocking synchronization is possible for hash table operations
  - But still expensive, even for read-only operations
- Consider concurrent lookup and remove operations:



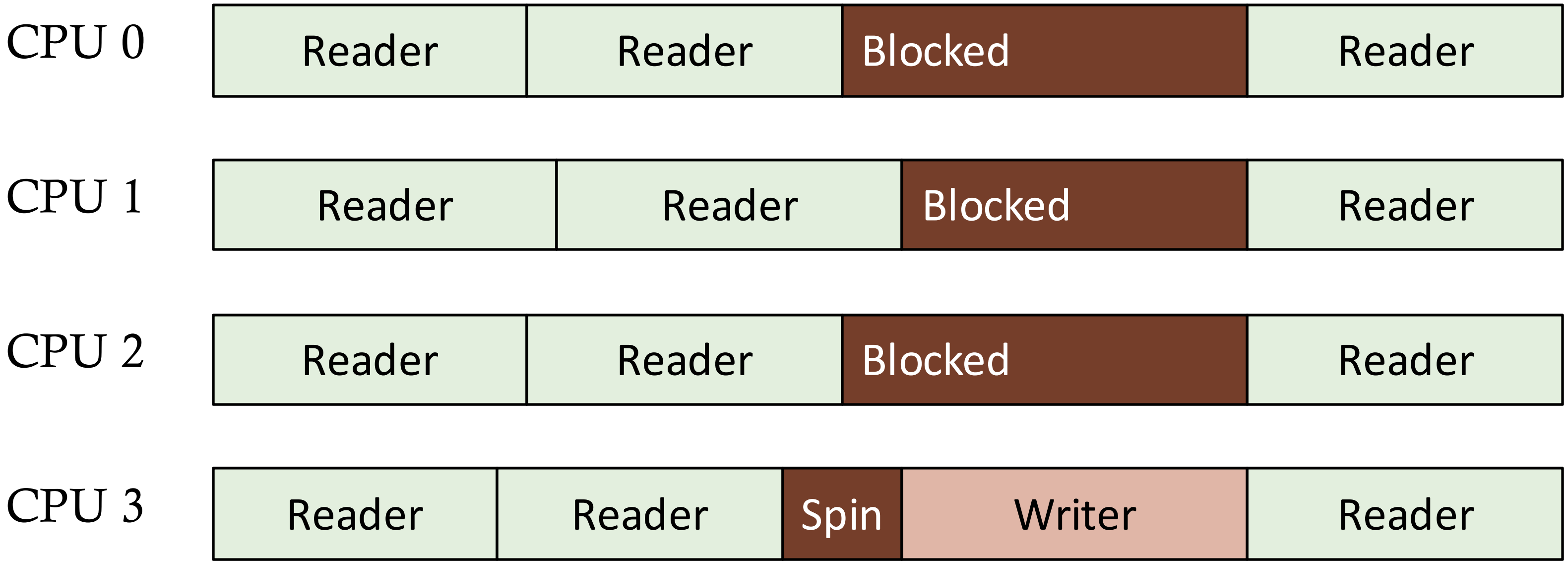
Reference Counting Solution

- T1 can increment reference count on N
  - Requires atomic update for each node along path to N on a read!
- T2 must defer deletion of a node with elevated reference count



Reader/Writer locks?

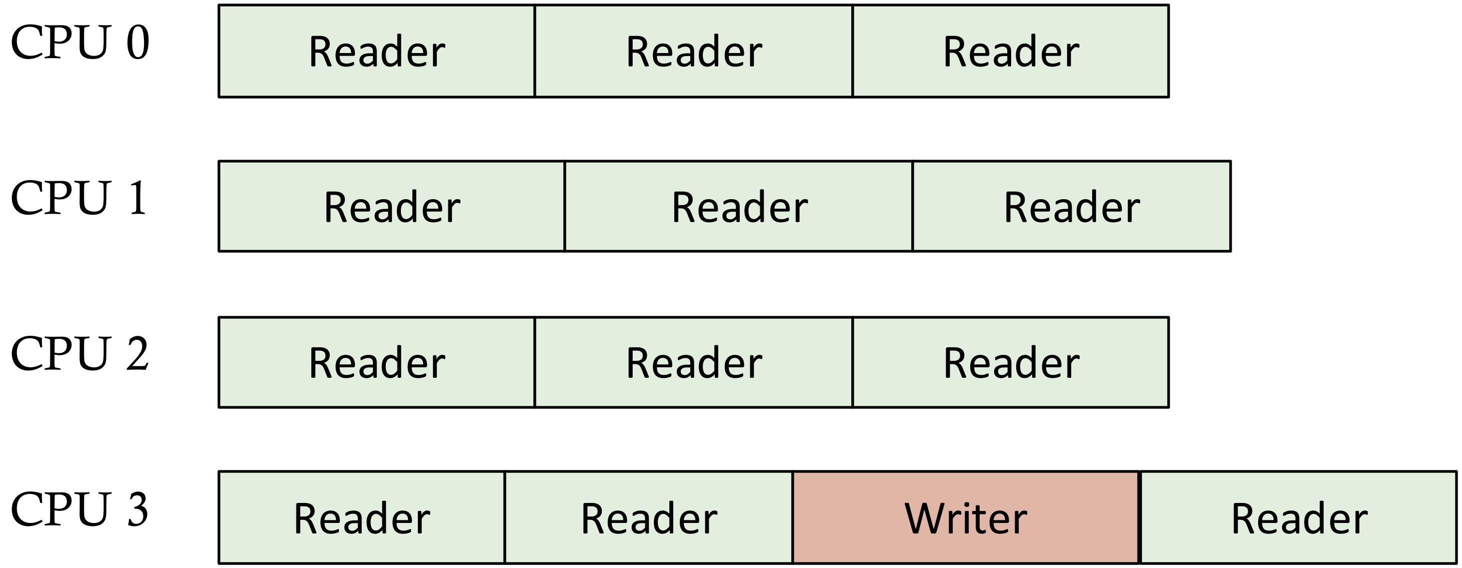
- Concurrent reads, exclusive writes



- Lots of "dead time" as all readers wait for single writer to finish

RCU Design Principle

- Avoid mutual exclusion!



- No more "dead time"
- But how can this be implemented?

RCU Basics

- Three key ideas
  - Use publish/subscribe ordering mechanism
    - Orders operations so readers see consistent, atomic updates
  - Maintain multiple versions of recently updated objects
    - Ensures readers that are concurrent with writers will read consistent (but perhaps stale) data versions
  - Wait for previous readers to complete
    - For deleting old versions
- All three together ensure that reads can be performed correctly without using locks
- See LWN article: http://lwn.net/Articles/262464

Understanding the Need for Publish/Subscribe

```
/* definitions */
struct foo {
  int a;
};

/* gp == global ptr */
struct foo *gp = NULL;
```

```
T1 (Writer):
  p = malloc(sizeof(*p));
  p->a = 1;
  gp = p;   // gp can be read by others
```

```
T2 (Reader):
  retry:
  p = gp; // get ptr to shared data
  if (p == NULL)
    goto retry;
  use(p->a);
```

- No locks are being used by reader
- When is it safe to dereference the gp pointer, i.e., is use(p->a) guaranteed to return 1?

Memory Order "Writer Mischief"

Compiler, CPU can reorder memory assignments and reads

```
T1 (Writer):
  p = malloc(sizeof(*p));
  p->a = 1;
  gp = p;
```

Problem 1

```
T1 (Writer):
  p = kmalloc(sizeof(*p));
  gp = p;
  p->a = 1;
```

```
T2 (Reader):
  retry:
  p = gp; // get ptr to shared data
  if (p == NULL)
    goto retry;
  use(p->a);  // may read unitialized value!
```

Memory Order “Reader Mischief”

Compiler, CPU can reorder memory assignments and reads

```
T1 (Writer):
  p = malloc(sizeof(*p));
  p->a = 1;
  gp = p;   // gp can be read by others
```

```
T2 (Reader):
  retry:
  p = gp;
  if (p == NULL)
    goto retry;
  use(p->a);
```

Problem 2 ⇒

```
T2 (Reader):
  retry:
  p = guess(gp);
  use(p->a); // old value
  if (p != gp)  // fails!
    goto retry;
```

RCU Publish/Subscribe Ordering Mechanism

```
/* definitions */
struct foo {
  int a;
};

/* gp == global ptr */
struct foo *gp = NULL;
```

```
T1 (Writer):
  p = malloc(sizeof(*p));
  p->a = 1;
  gp = p; rcu_assign_pointer(gp,p);
```

```
T2 (Reader):
  retry
  p = gp; p = rcu_dereference(gp);
  if (p == NULL)
    goto retry;
  use(p->a);
```

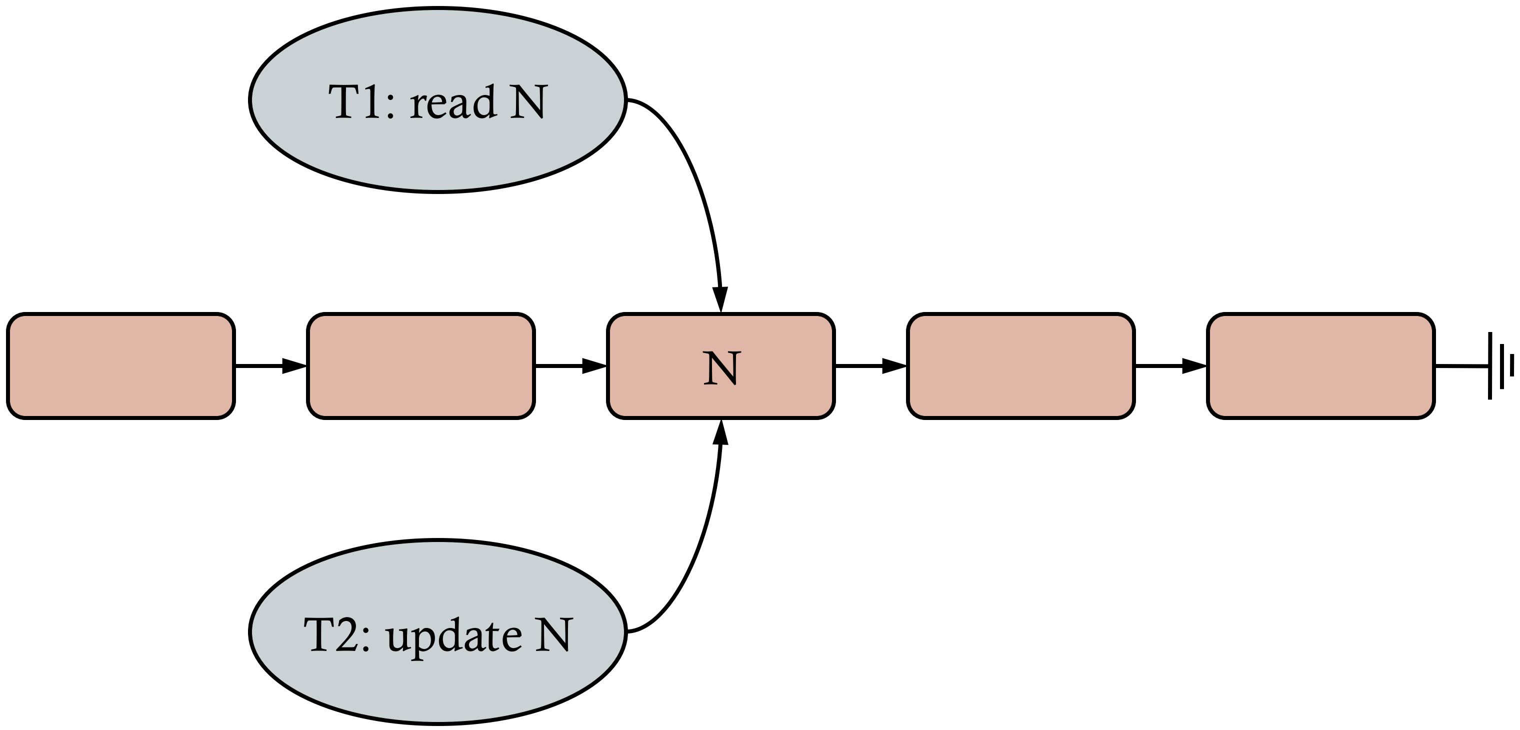
- Enforce ordering with rcu_assign_pointer/rcu_dereference
  - They encapsulate memory barriers, ensuring the correct ordering

Maintaining Multiple Versions

- Two examples using linked list
  - Update
  - Deletion

RCU List Element Update

- T1 traversing linked list, T2 updates an element:



RCU List Element Update

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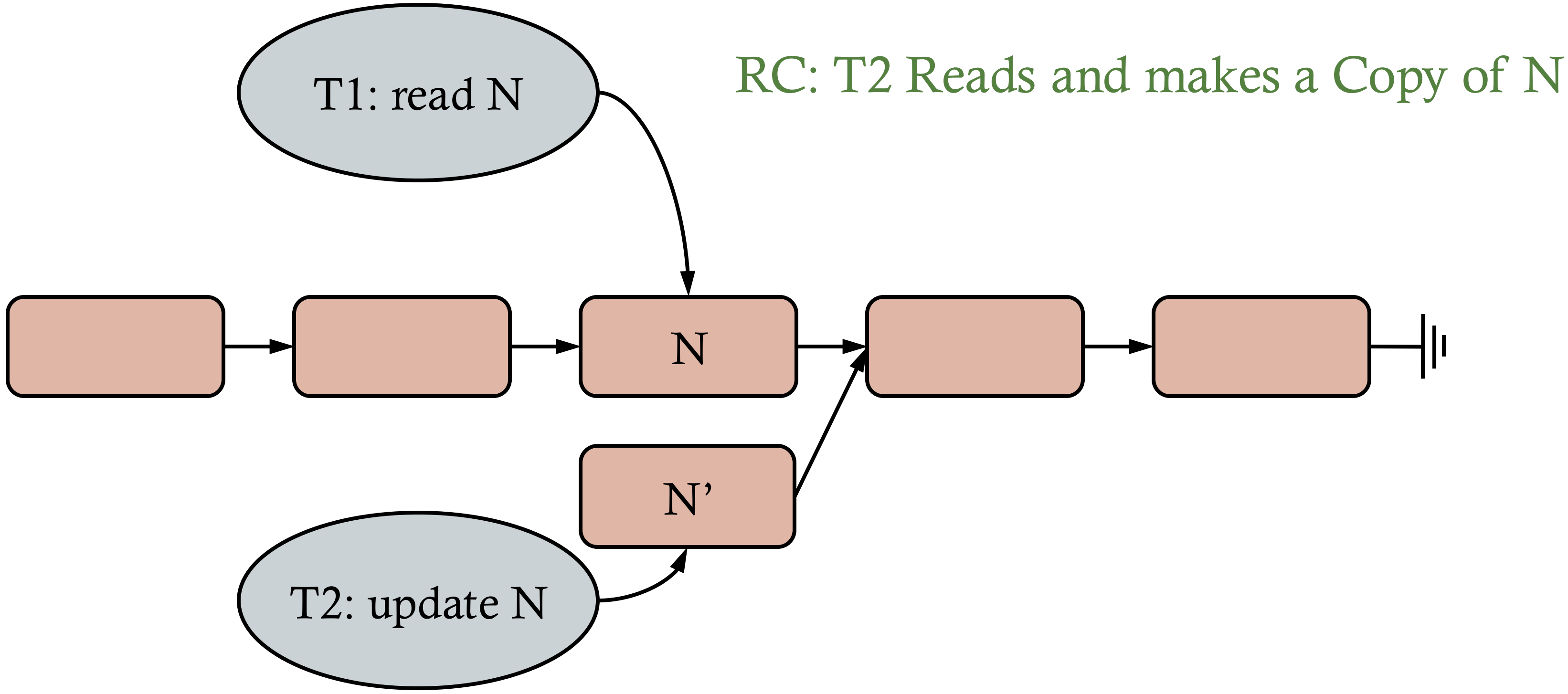
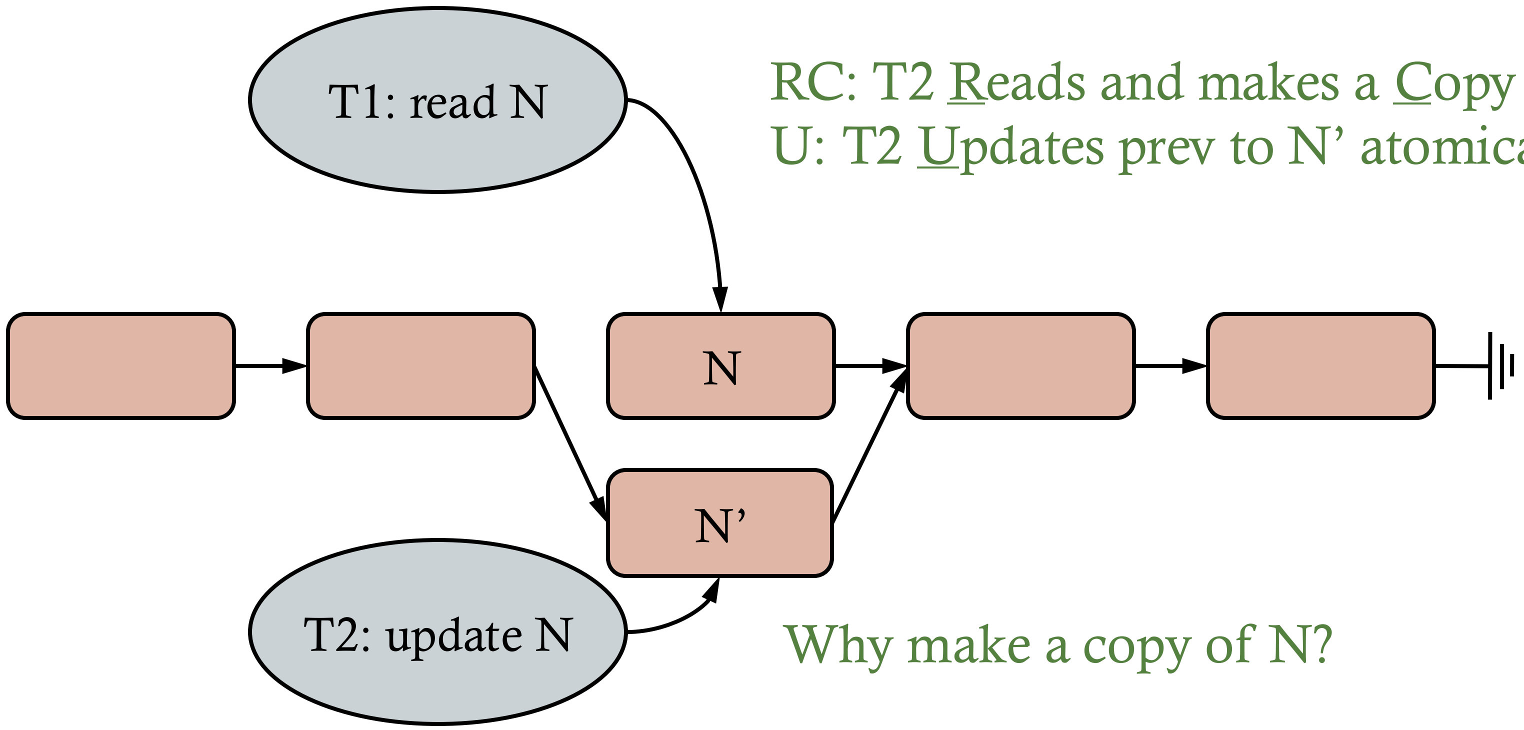


RCU List Element Update

- T1 traversing linked list, T2 updates an element:



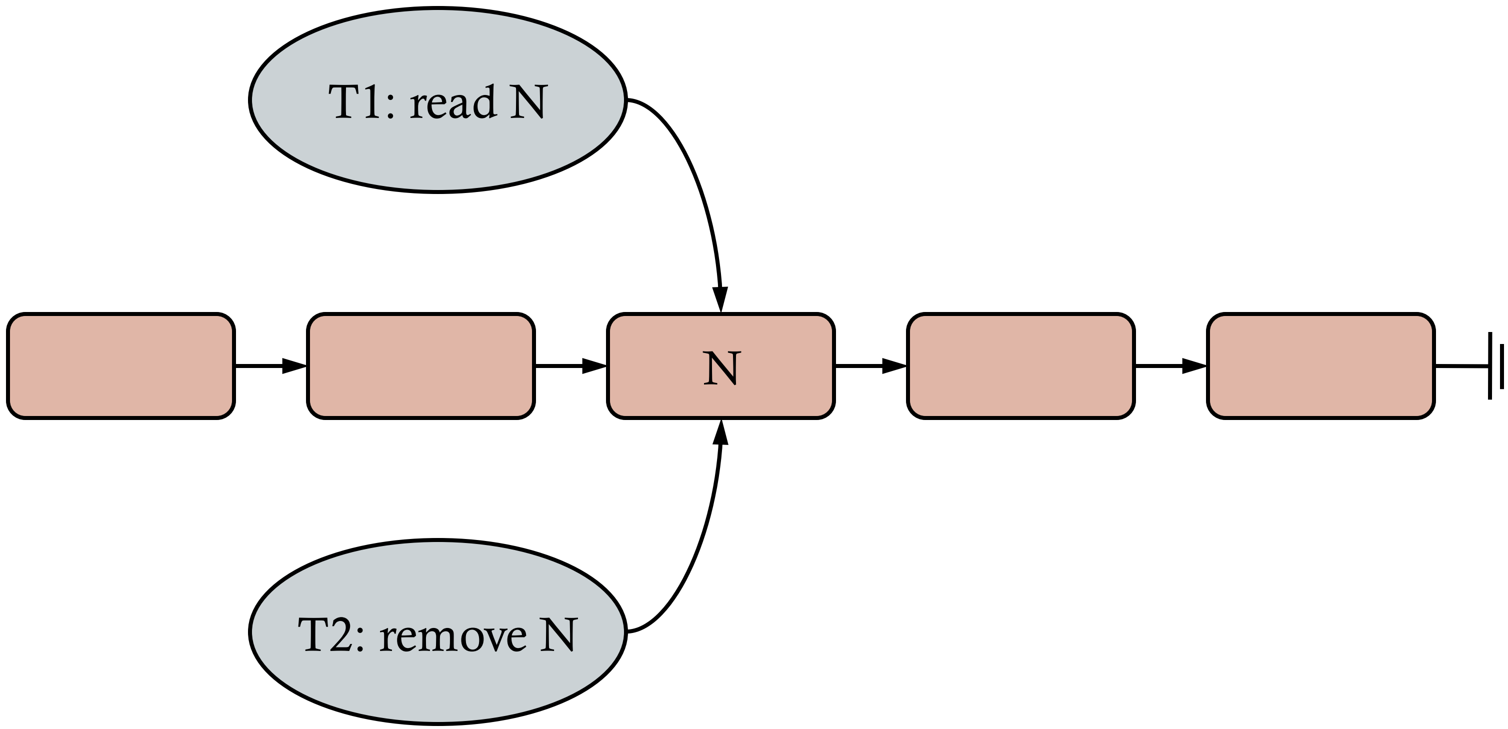
RC: T2 Reads and makes a Copy of N
U: T2 Updates prev to N’ atomically

Why make a copy of N?

When is it ok to delete N (and reuse the memory for something else)?

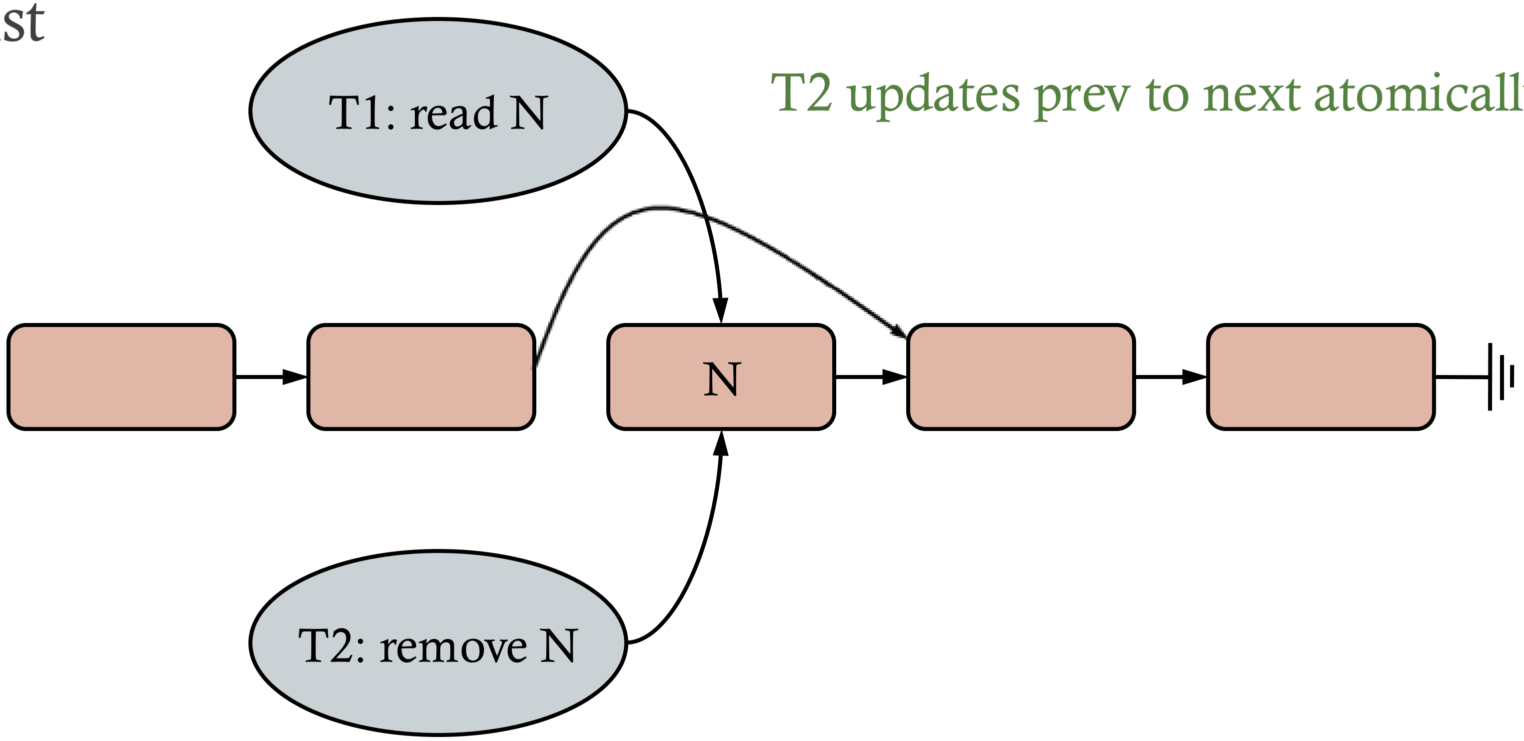
RCU List Element Deletion

- T1 traversing linked list, T2 removes an element:



RCU List Element Deletion

- After removal – T1 continues to use N and later nodes in the list

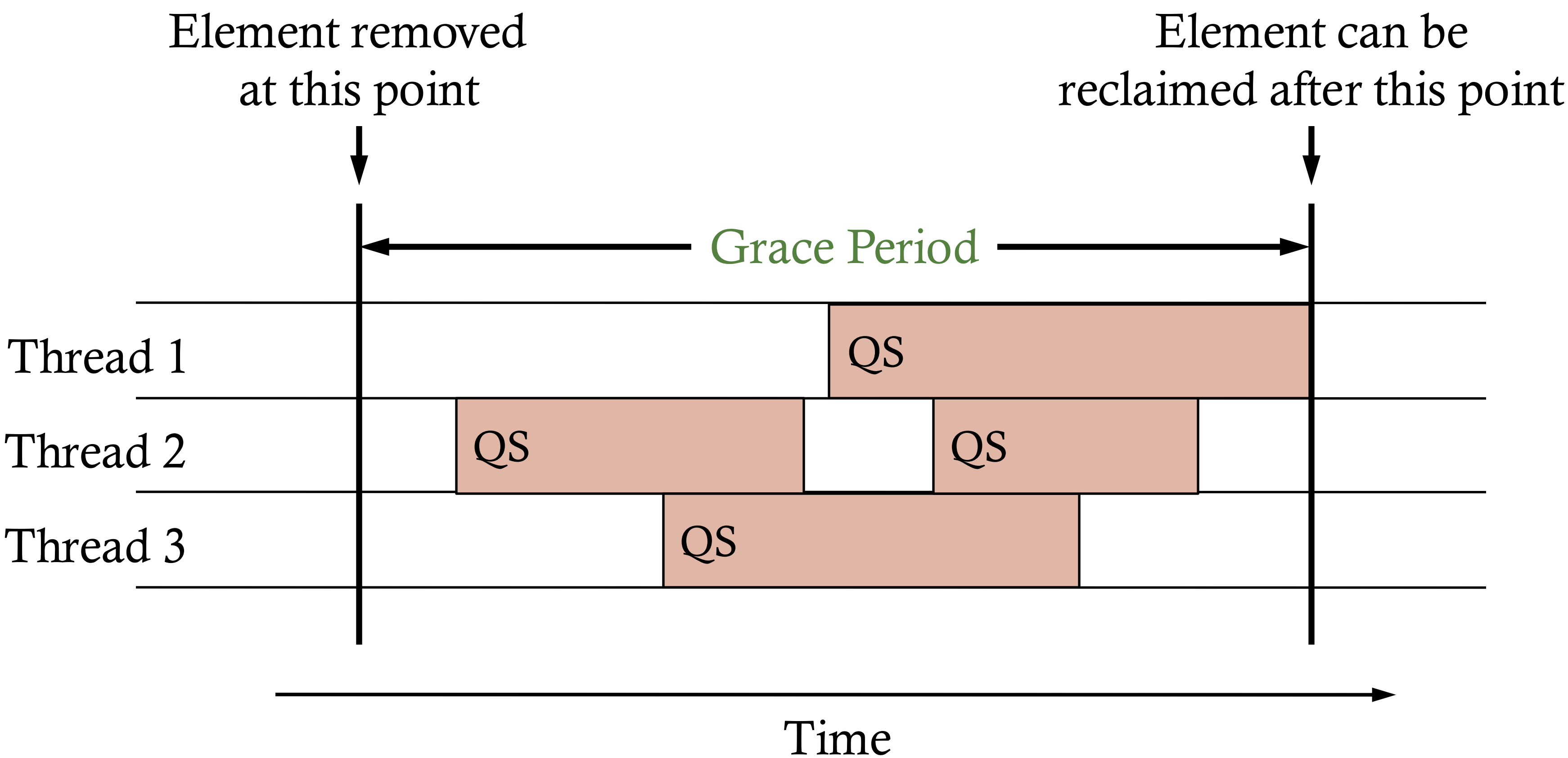


When is it ok to delete N (and reuse the memory for something else)?

Waiting for Previous Readers

- RCU needs to wait for previous readers to reclaim old versions
- RCU uses quiescent-state based reclamation (QSBR) to handle these read-reclaim races
- Definition: A quiescent state for a thread T is a state in which T holds no references to any shared data
- Definition: A grace period is an interval in which every thread has passed through at least one quiescent state
- QSBR idea: elements removed from a data structure can be reclaimed after a grace period, since no thread can still be holding a reference to the old element at that point

Illustration



How to define Quiescent States?

- Application dependent!
- For OS kernels, some natural ones exist
  - Assume that references to RCU data structures are only held within read or write critical sections
    - Read critical section: thread reads an RCU-protected data structure
    - Write critical section: thread writes an RCU-protected data structure
  - Assume that read critical sections do not block
    - i.e., No context switch occurs within a read-side critical section
  - Then, a context switch is a quiescent state
    - No references are held across a context switch

Reader-Side Quiescence Primitives: Read Lock/Unlock

```
/* definitions */
struct foo {
  int a;
};

/* gp == global ptr */
struct foo *gp = NULL;
```

```
T1 (Writer):
  p = malloc(sizeof(*p));
  p->a = 1;
  rcu_assign_pointer(gp, p);
  // when can we free(p)?
```

```
T2 (Reader):
rcu_read_lock(); // notice, no lock var
p = rcu_dereference(gp);
  if (p != NULL)
    use(p->a);
rcu_read_unlock();
```

lock/unlock do not spin or block!

- `rcu_read_lock/unlock` disable context switch within read-side critical section
- Write can detect that read is in progress (reader is not quiescent) and does not delete data that is being accessed by reader

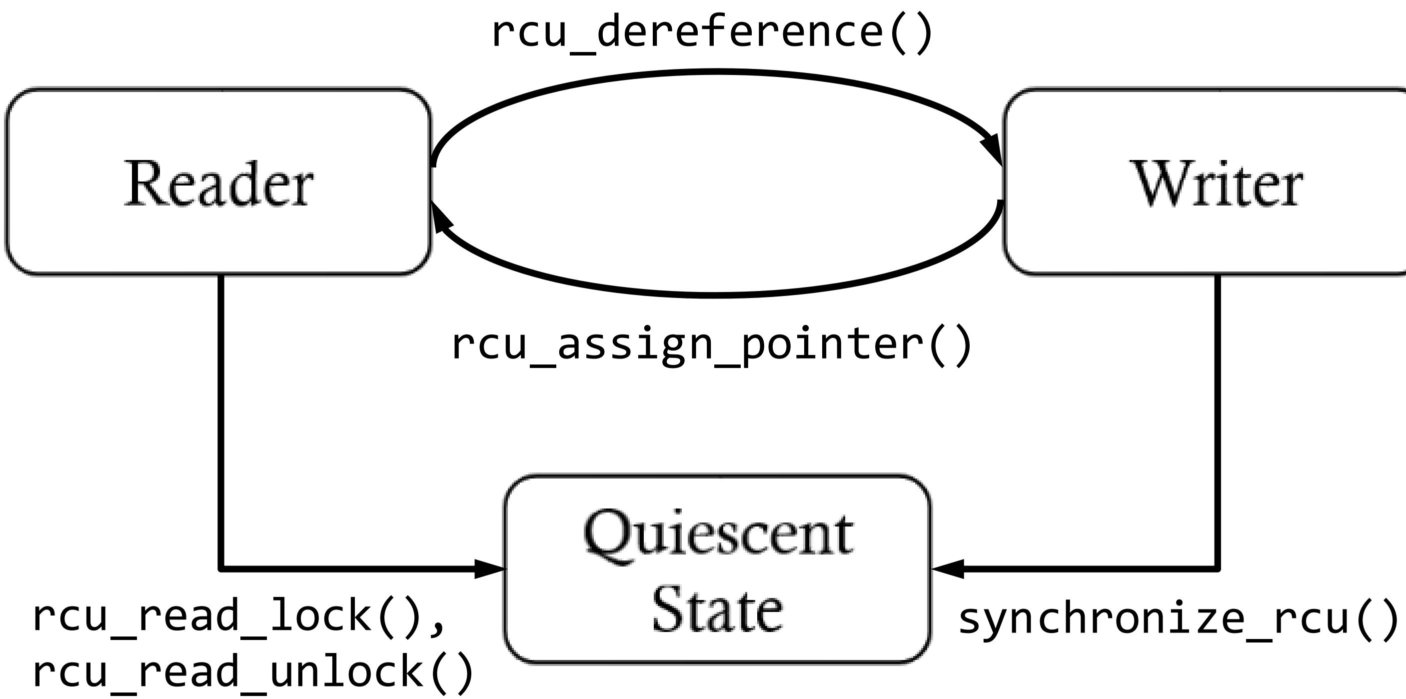
Writer-Side Quiescence Primitive: Synchronize RCU

- `synchronize_rcu()`
  - Wait until all pre-existing RCU read-side critical sections complete
- Implementation:

```
synchronize_rcu() {
    for_each_online_cpu(cpu)
        run_on(cpu); // runs the current thread on cpu
}
```

- `synchronize_rcu()` runs the current thread on all CPUs
  - Forces context switches on each of the CPUs
  - Ensures that it waits for the grace period

RCU Synchronization



Linux RCU List Update Code

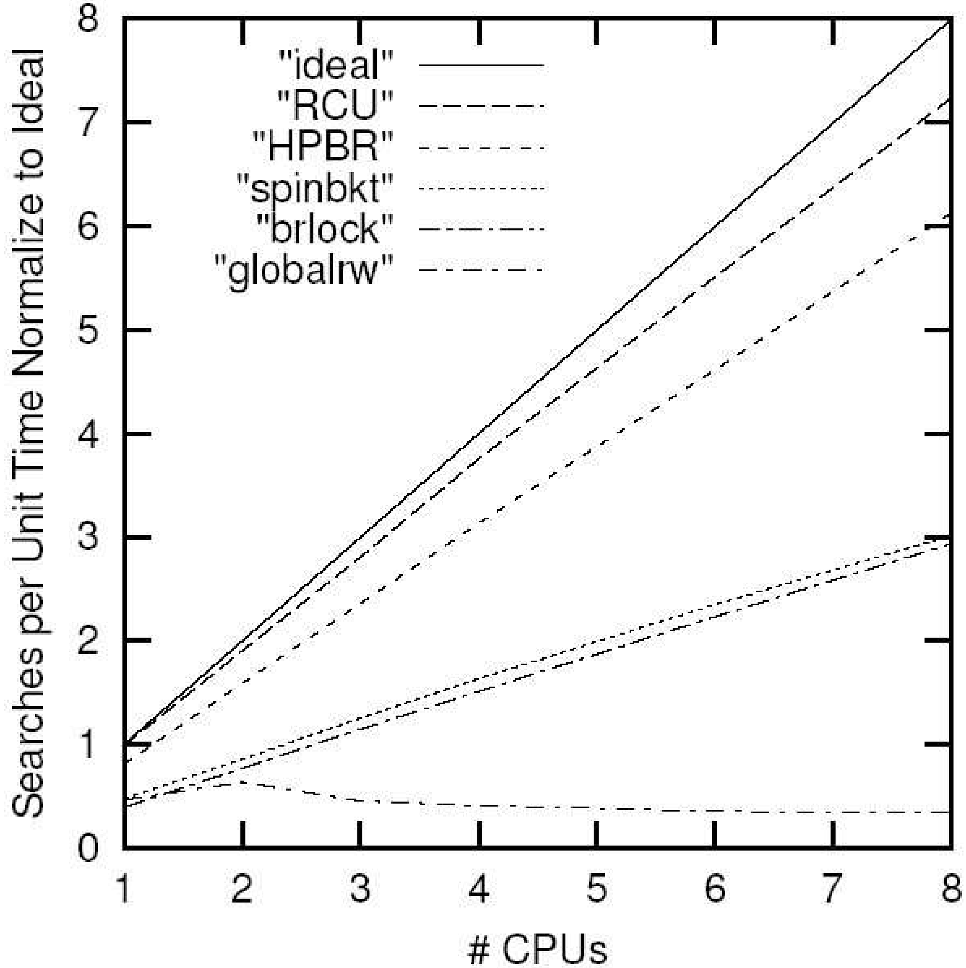
```
// Reader traverses
// a linked list

rcu_read_lock();
// next line uses
// rcu_dereference
hlist_for_each_entry_rcu(p,
    q, head, list) {
    // p is a linked
    // list node
    do_something(p->value);
}
rcu_read_unlock();
```

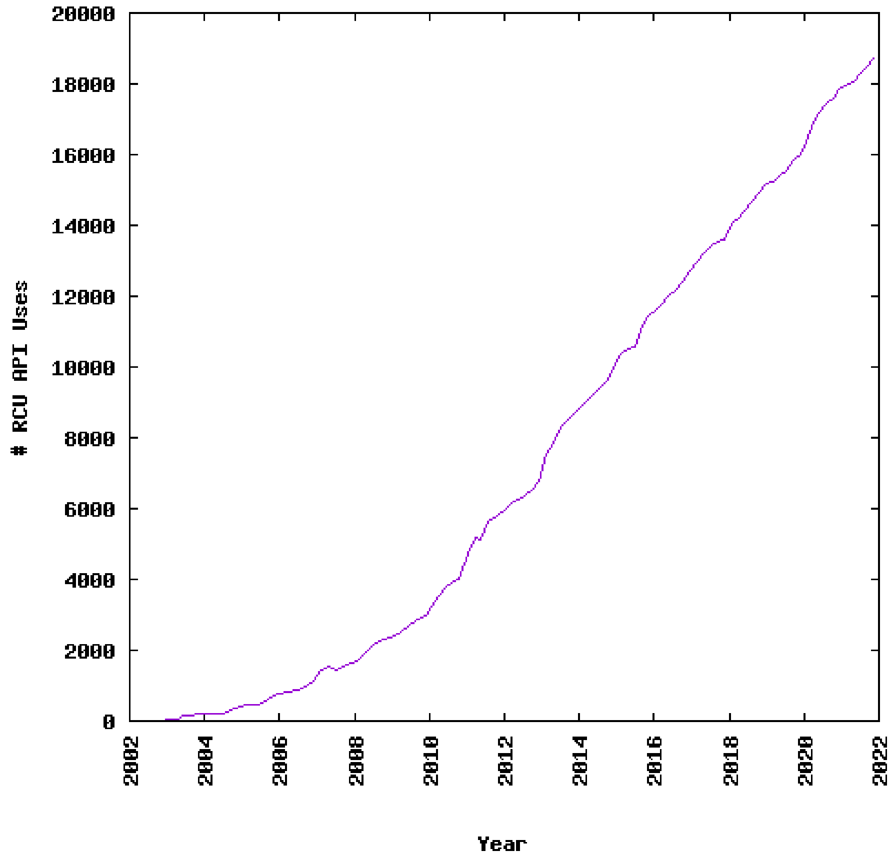
```
// Writer searches and updates
// a list element

p = search(head, key);
if (p == NULL) {
    /* unlock and return. */
}
q = kmalloc(sizeof(*p), GFP_KERNEL);
*q = *p; // read and copy
q->value = ...;
// atomically replace p with q
// next line uses rcu_assign_pointer
list_replace_rcu(&p->list, &q->list);
// wait for grace period
synchronize_rcu();
// free previous version
kfree(p);
```

PPC Hash Table with RCU

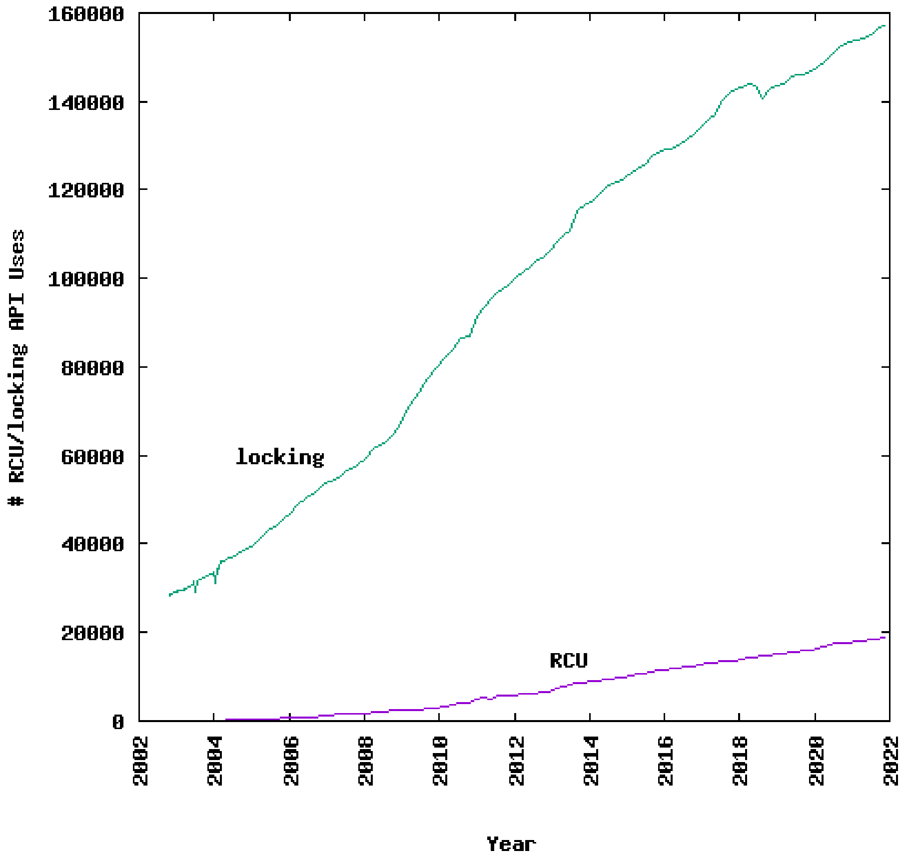


Growth of RCU Use in Linux



Graph from http://www.rdrop.com/users/paulmck/RCU/linuxusage.html
(Nov 26, 2021, generated daily)

…but Still Small in Comparison



Graph from http://www.rdrop.com/users/paulmck/RCU/linuxusage.html
(Nov. 26, 2021, generated daily)

When to Use Which Tool?

- Read-mostly situations
  - If algorithm can handle concurrent reads + single updater: RCU
- Update-heavy situations
  - Simple data structures and algorithms: NBS
  - Complex data structures and algorithms: Locking
- When you only have a hammer, everything looks like a nail
- It's good to have lots of tools in your toolbox!

Some Resources

- LWN article on lockless algorithms
  https://lwn.net/Kernel/Index/#Lockless_algorithms
- Load dependent ordering behavior in Alpha:
  http://www.cs.umd.edu/~pugh/java/memoryModel/AlphaReordering.html
- An excellent book on multi-processor synchronization and lockless algorithms: The art of multiprocessor programming by Maurice Herlihy & Nir Shavit