Read-Copy Update

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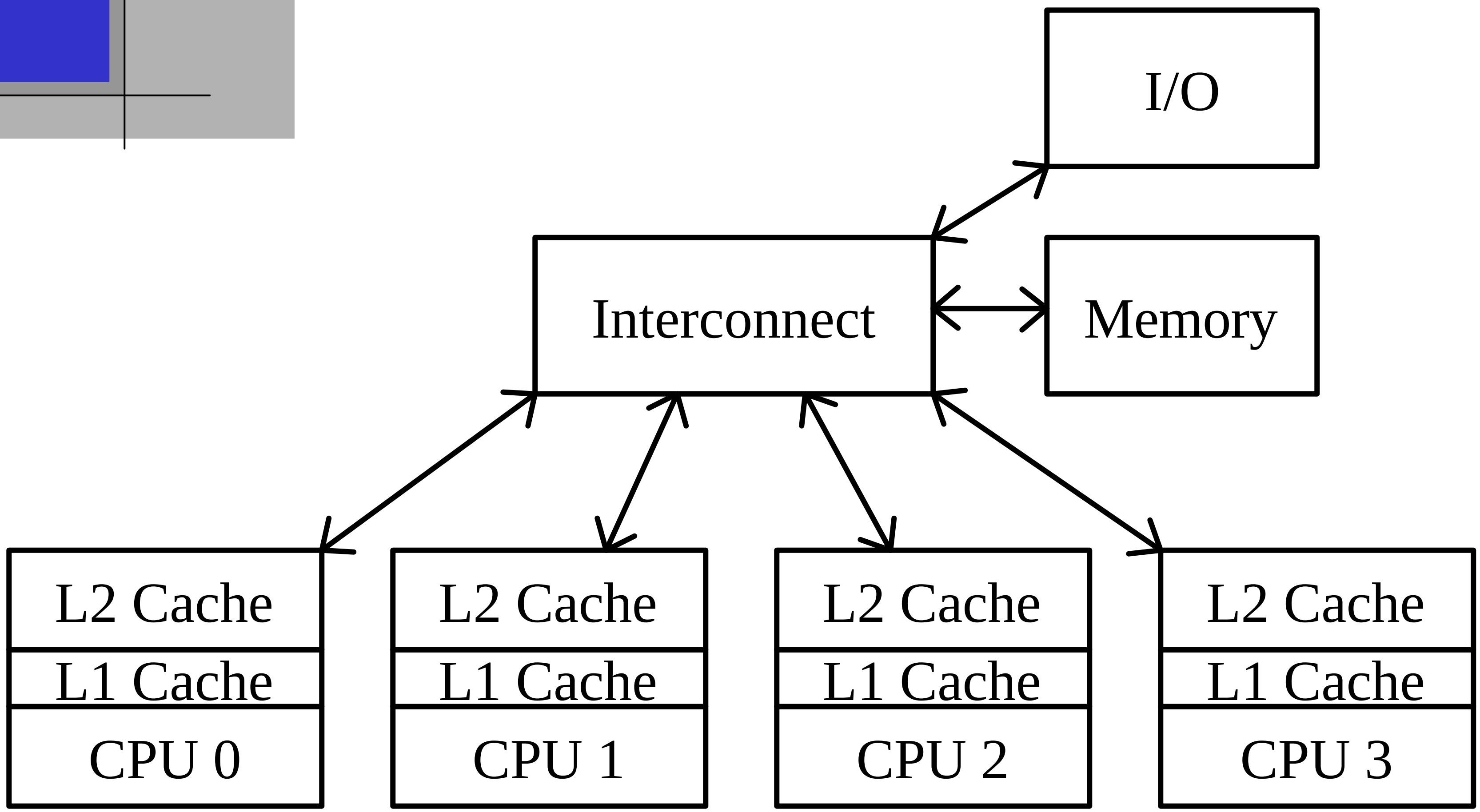
Goal

- Simple, high-performance and -scaling algorithms for read-mostly situations
  - Readers must *not* be required to acquire locks, execute atomic operations, or disable interrupts
    - Read-side code same as UP user-level implementation
    - Want performance to scale with CPU core clock rate, *not* with memory latency
  - OK if writers have to do a *little* more work
- Focus on non-preemptive OS kernel

Overview

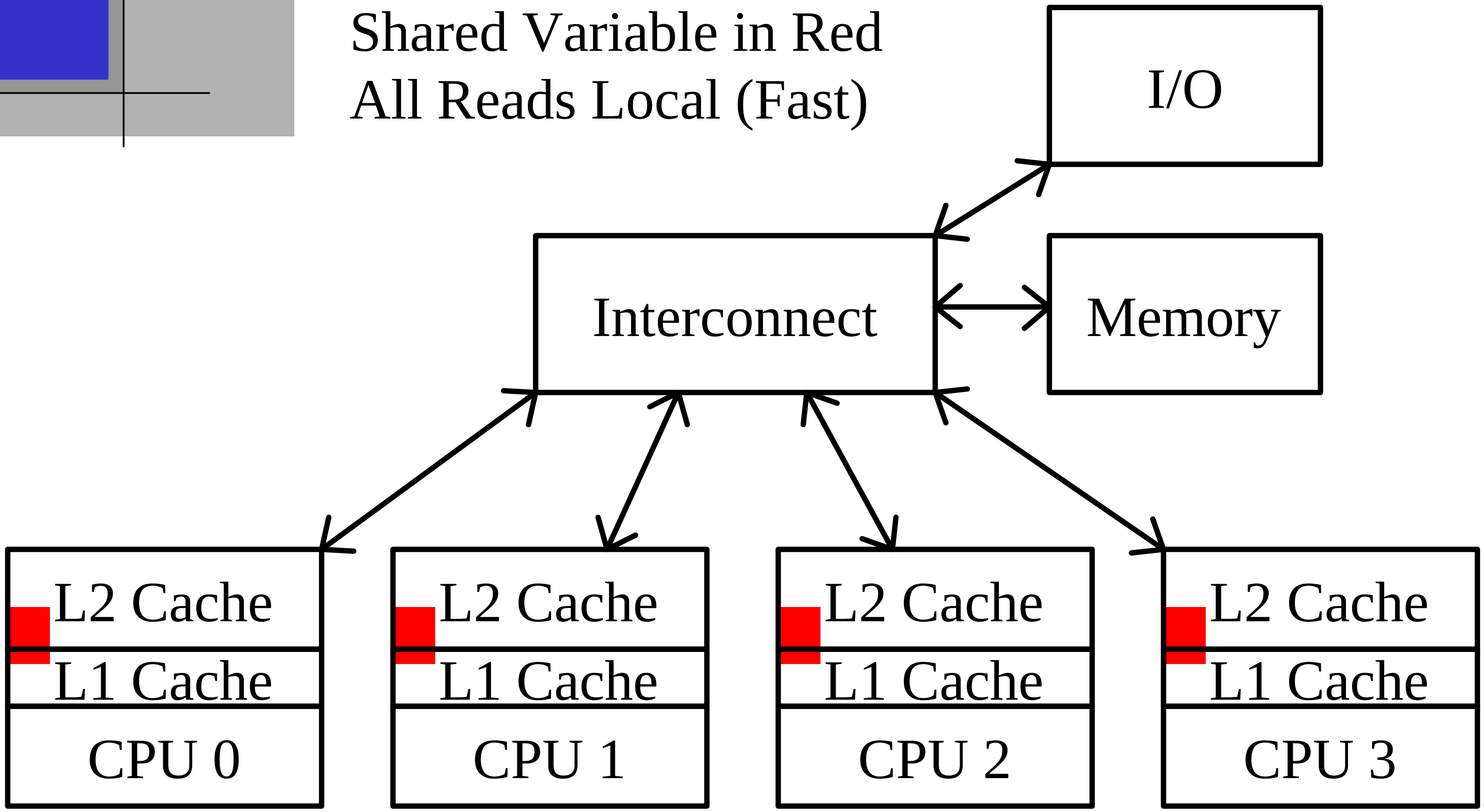
- *Why is this goal important?*
- How the $#@#!! can readers safely access a changing data structure without locking???
  - Without writers needing a gazillion cycles to perform an update?
- Does this really help in real-world code?

Current CPU-Memory Architectures



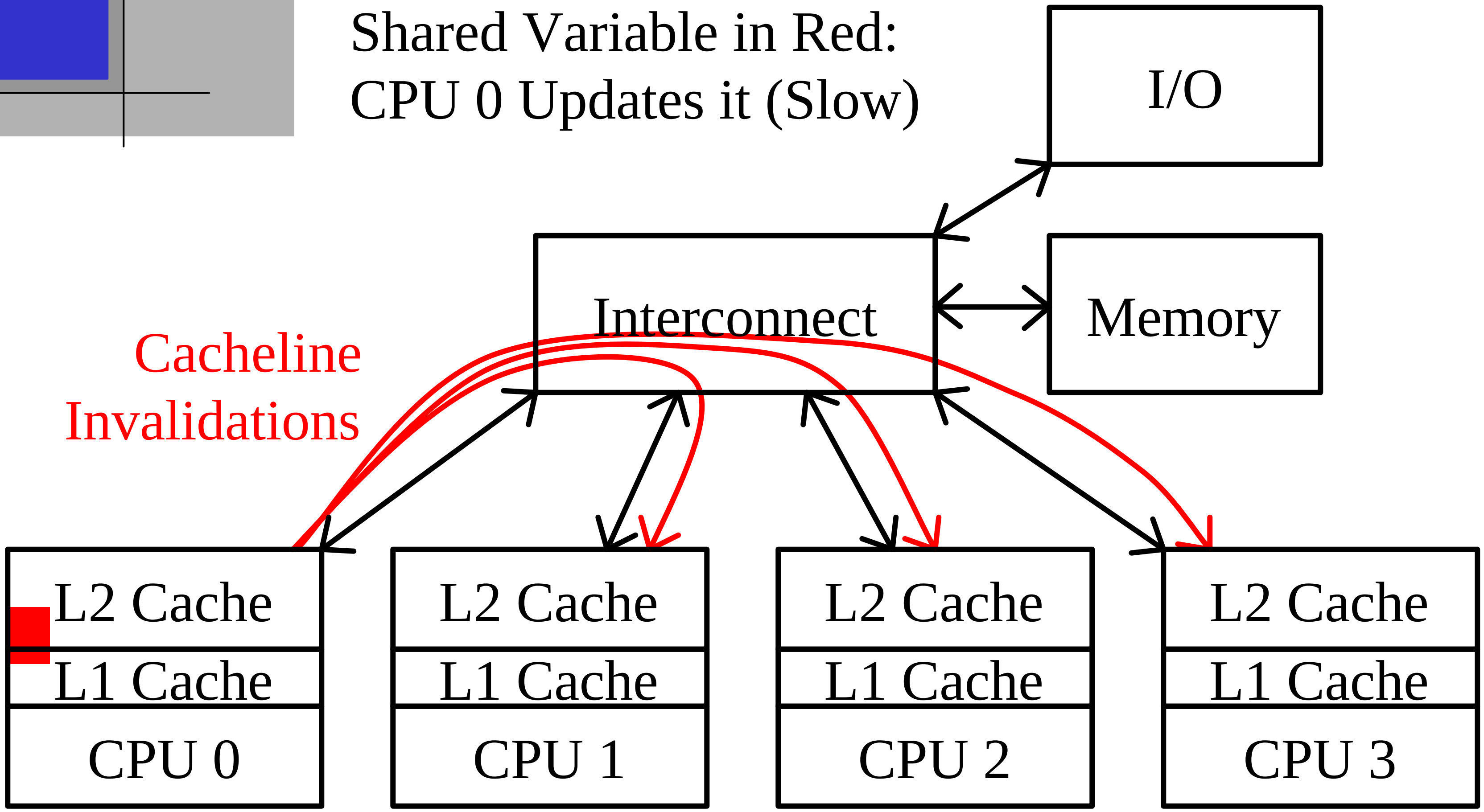
Current CPU-Memory Architectures

Shared Variable in Red
All Reads Local (Fast)



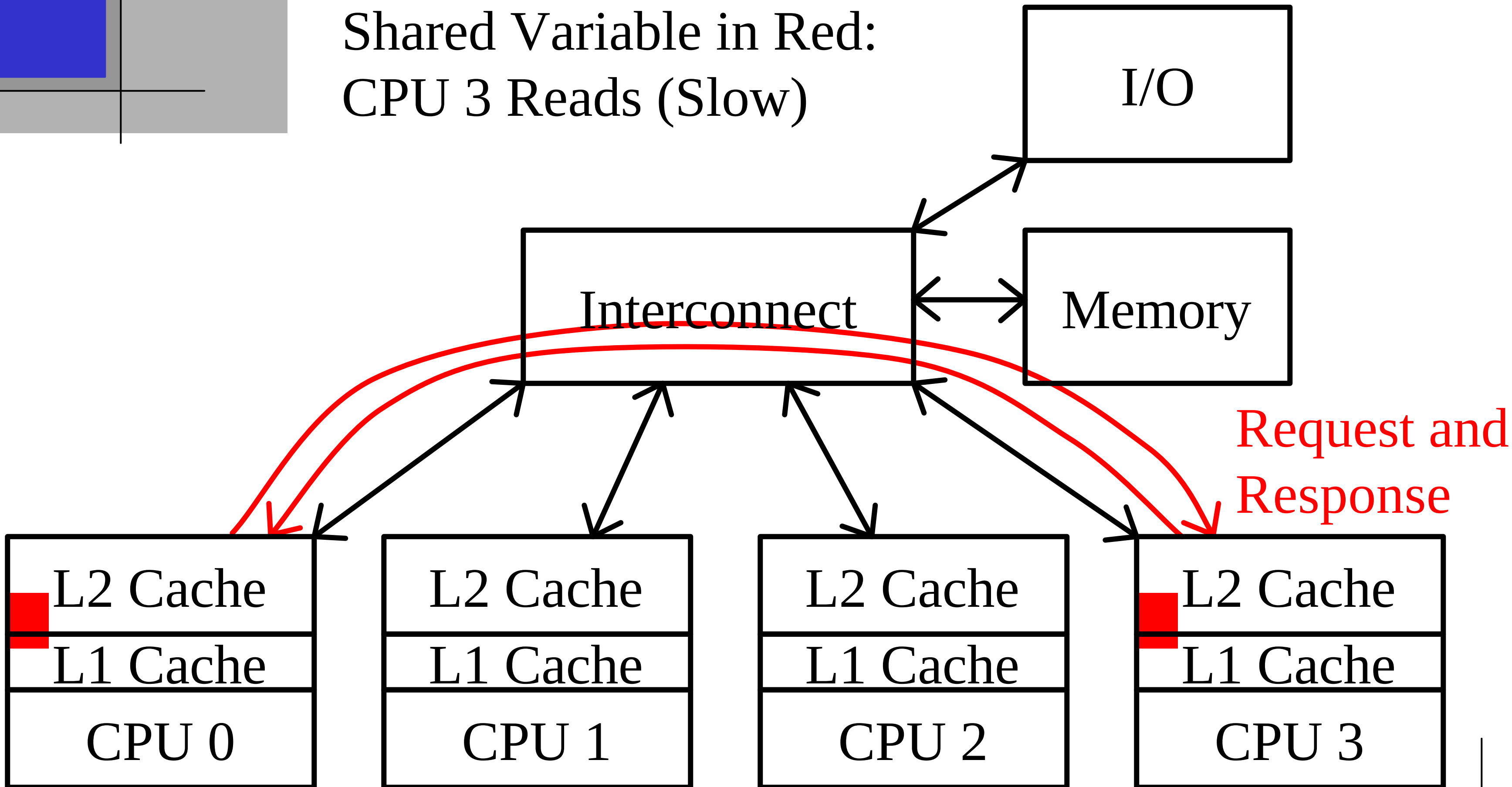
Current CPU-Memory Architectures

Shared Variable in Red:
CPU 0 Updates it (Slow)

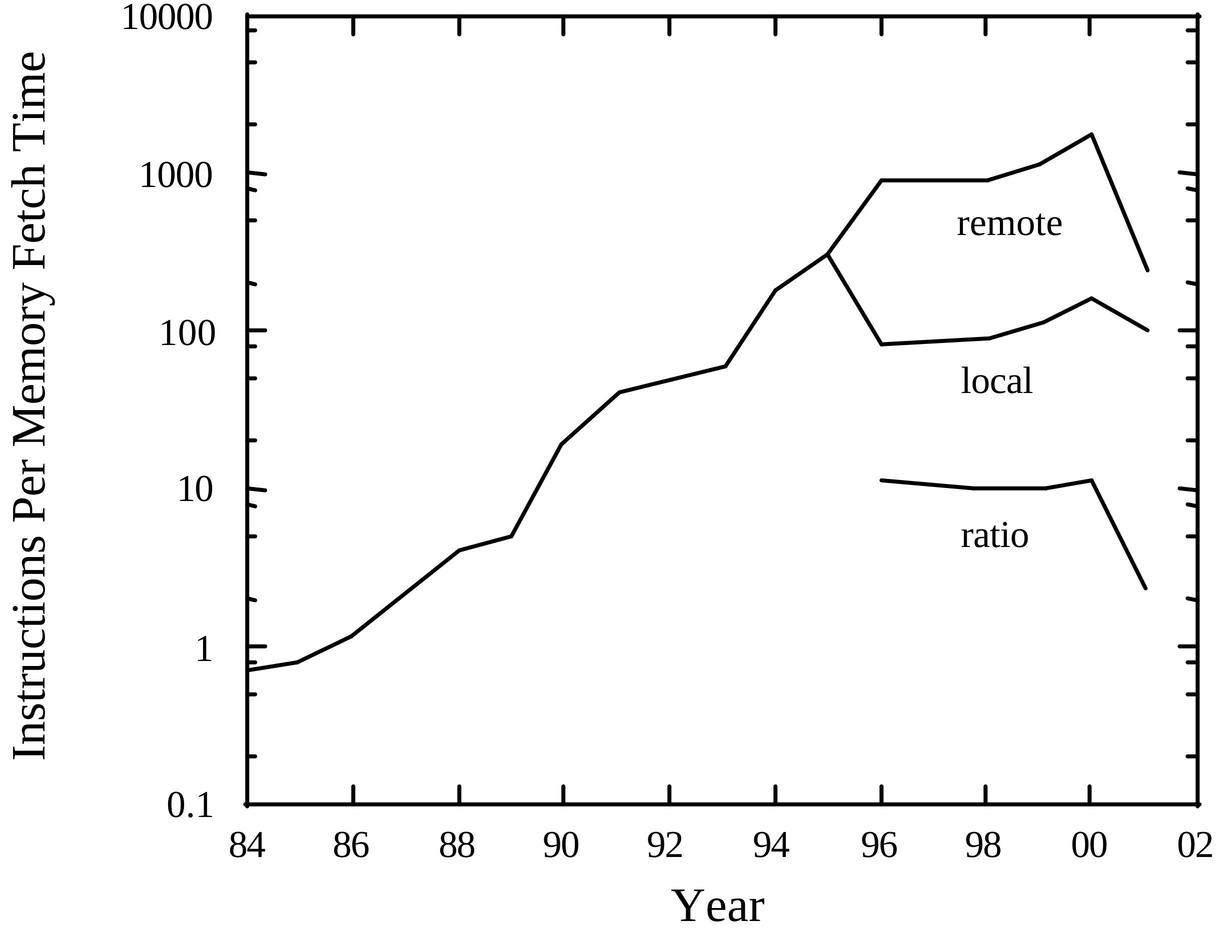


Current CPU-Memory Architectures

Shared Variable in Red:
CPU 3 Reads (Slow)

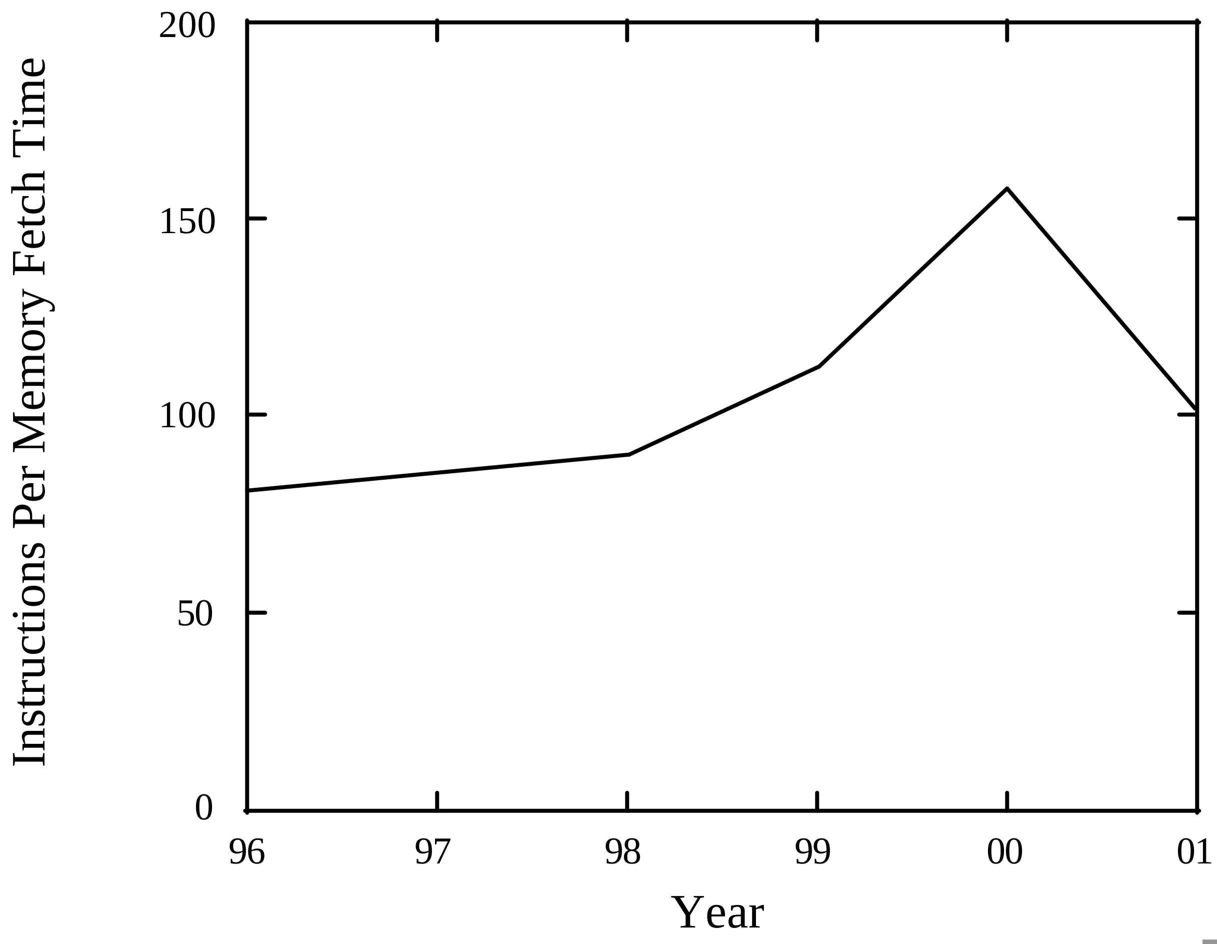


Long-Term Architectural Trends



Data from Sequent/IBM NUMA-Q Machines

Recent Architectural Trends



Global Locks and Reference Counts: >100-to-1 Hit!!!

Architectural-Trend Consequences

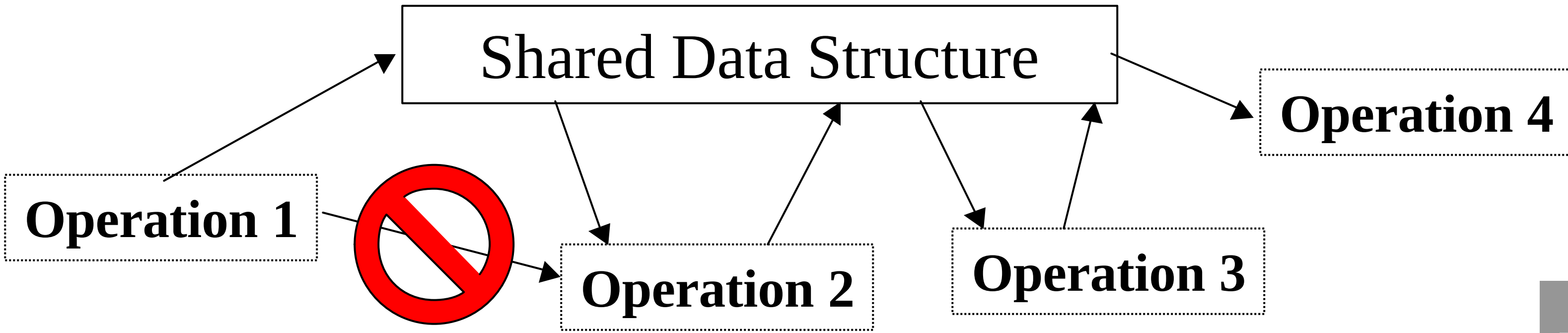
- Global locks becoming increasingly expensive
- Globally-used reference counters also becoming increasingly expensive
- *Would like some way for read-only accesses to read-mostly data structures to avoid locks and reference-count manipulation...*
  - *Take advantage of periodic nature of the Linux kernel*

Overview

- Why is this goal important?
- *How the $#@#!! can readers safely access a changing data structure without locking???*
  - Without writers needing a gazillion cycles to perform an update?
- Does this really help in real-world code?

Periodic Nature of Linux Kernel

- Execution divided into relatively short-duration “operations” with respect to shared data structure
- No “covert channels” between operations



What is an "Operation"???

Can Begin or End Anyplace
Where No Locks Are Held

- For non-preemptible kernels:
  - begin and end at a context switch
- For preemptible Linux kernels:
  - begin and end at a voluntary context switch
- For K42 research OS:
  - duration of K42's analog of syscall
- For this talk, focus on non-preemptible kernels

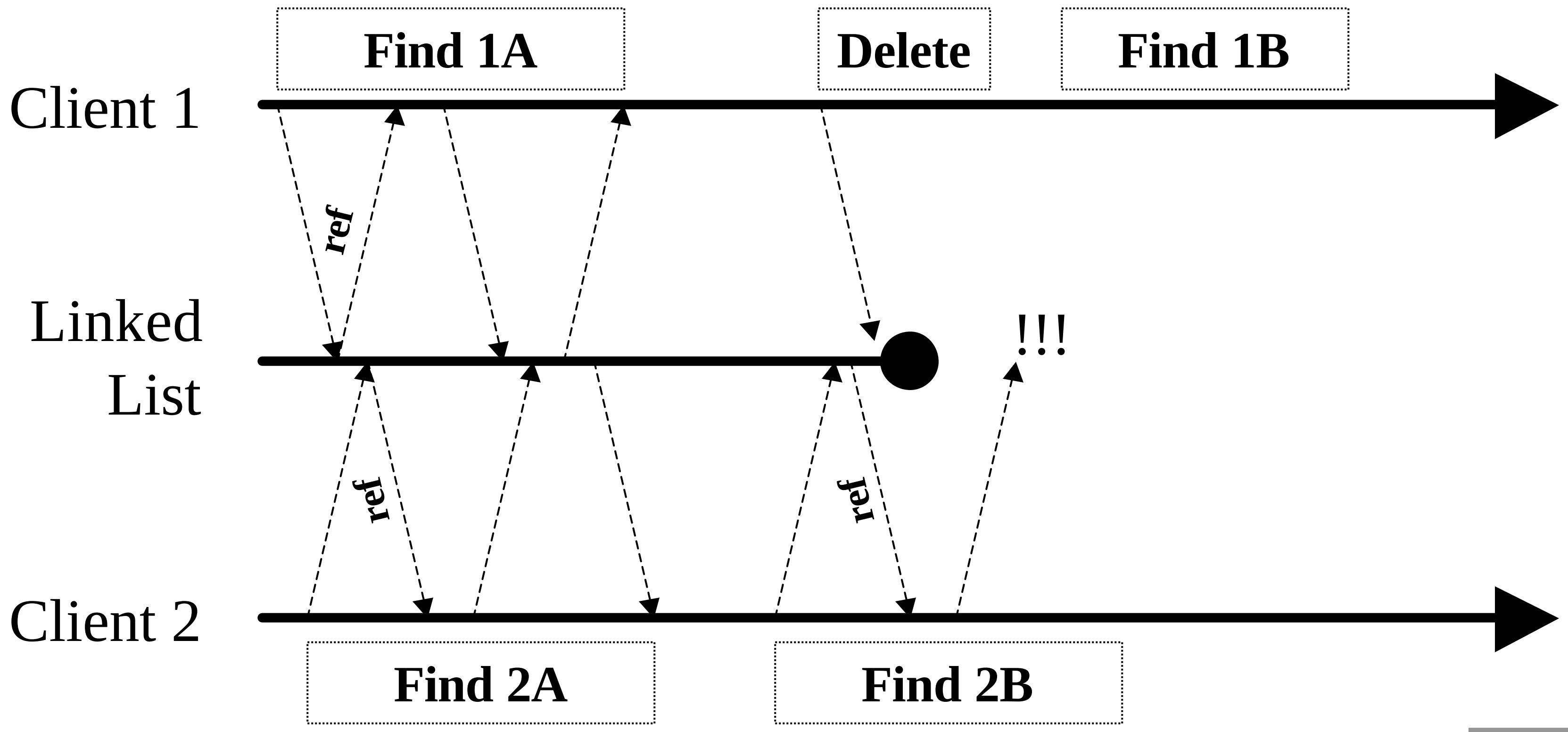
"No Covert Channels" & Locking

```
void really_bad_idea(void)
{
   struct foo *fp;

   spin_lock(&my_lock);
   fp = list_head;
   spin_unlock(&my_lock);

   /* Do some other stuff… */

   spin_lock(&my_lock);
   fp = fp->next;
   spin_unlock(&my_lock);
}
```

- "Covert channels" bad for locks
  - Just as bad for read-copy update
  - Drop locks, and whole world can change!

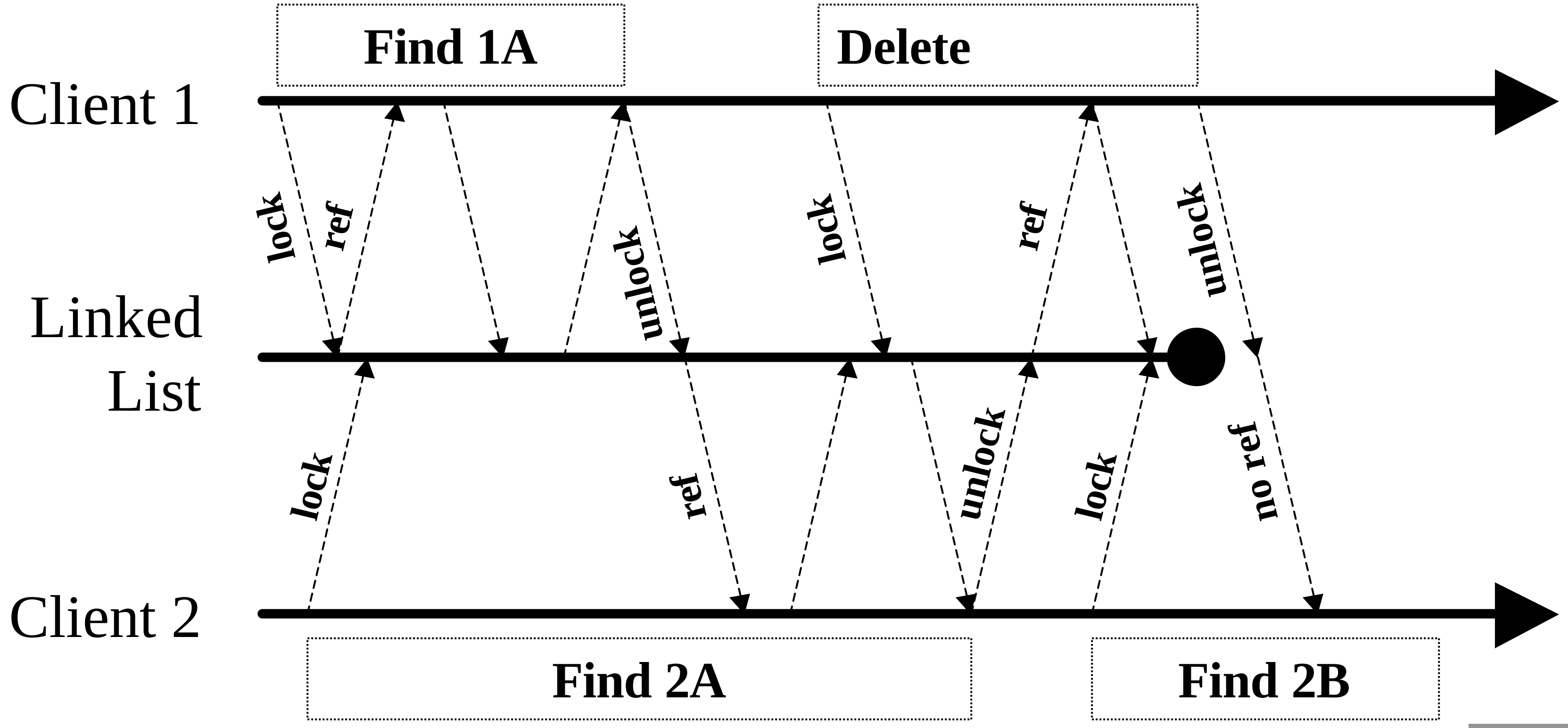
Example Problem

- Race between use and deletion of list element



Global Locks to the Rescue...

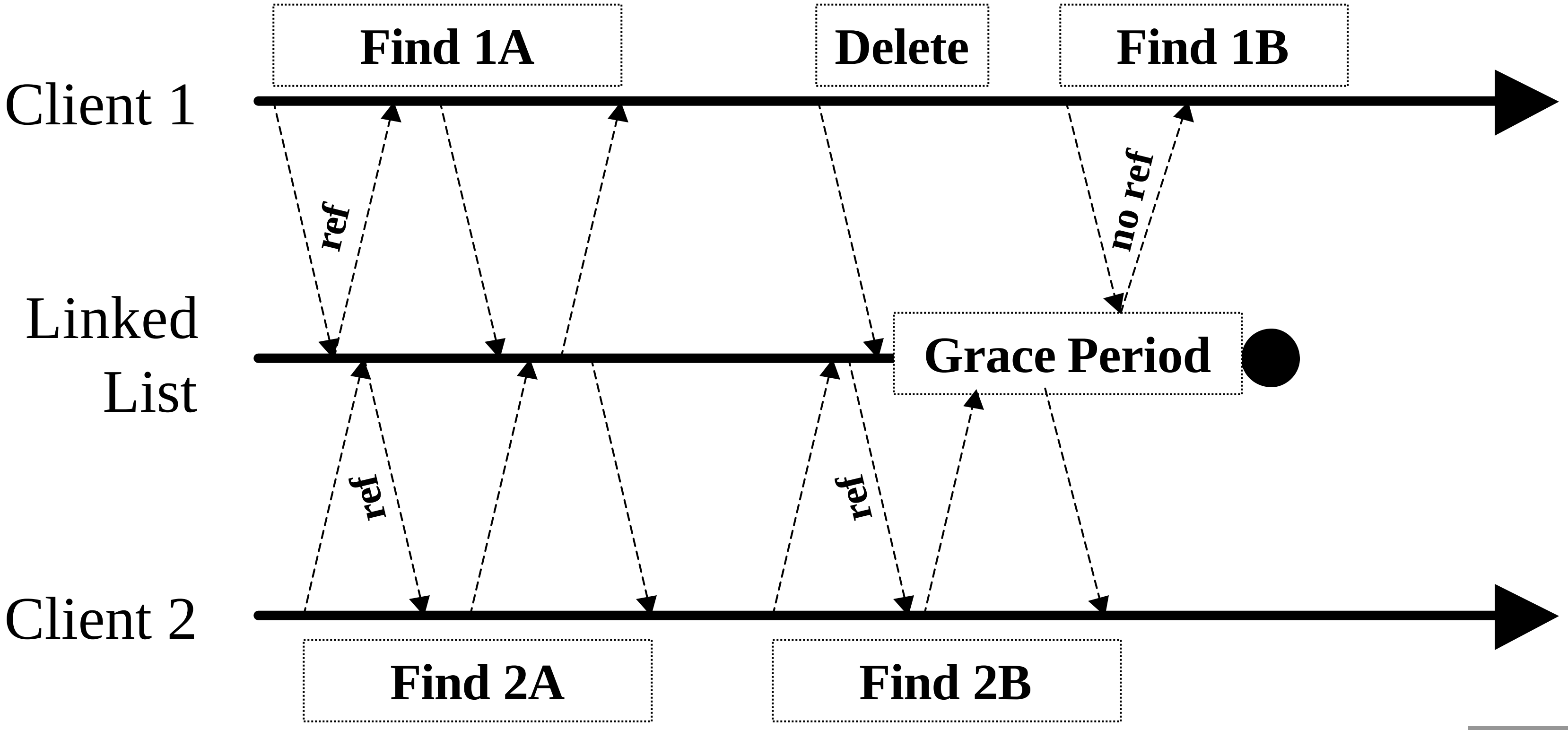
But rather slowly...



Reference Counts to the Rescue...

- Remember the architectural trends!!!
- Incrementing a shared reference count is ~100 times more expensive than a typical instruction!!!
- And the relative expense has been getting steadily worse over the past two decades.
- Sometimes must write to shared storage
  – But let's not do it gratuitously...

Read-Copy Update: Grace Period



Read-Copy Update

```
struct el *find(long key)
{
   struct el *p;
   p = head->next;
   while (p != head) {
      if (p->key == key) {
         return (p);
      }
      p = p->next;
   }
   return (NULL);
}
```

- Identical to single-threaded code
- No cache thrashing or spinning
  - *Scale with core CPU clock rate*

Read-Copy Update

```
void delete(struct el *p)
{
   struct el *p;

   lock(&list_updater_lock);
   p->next->prev = p->prev;
   p->prev->next = p->next;
   unlock(&list_updater_lock);

   wait_for_rcu();

   kfree(p);
}
```

Phase 1

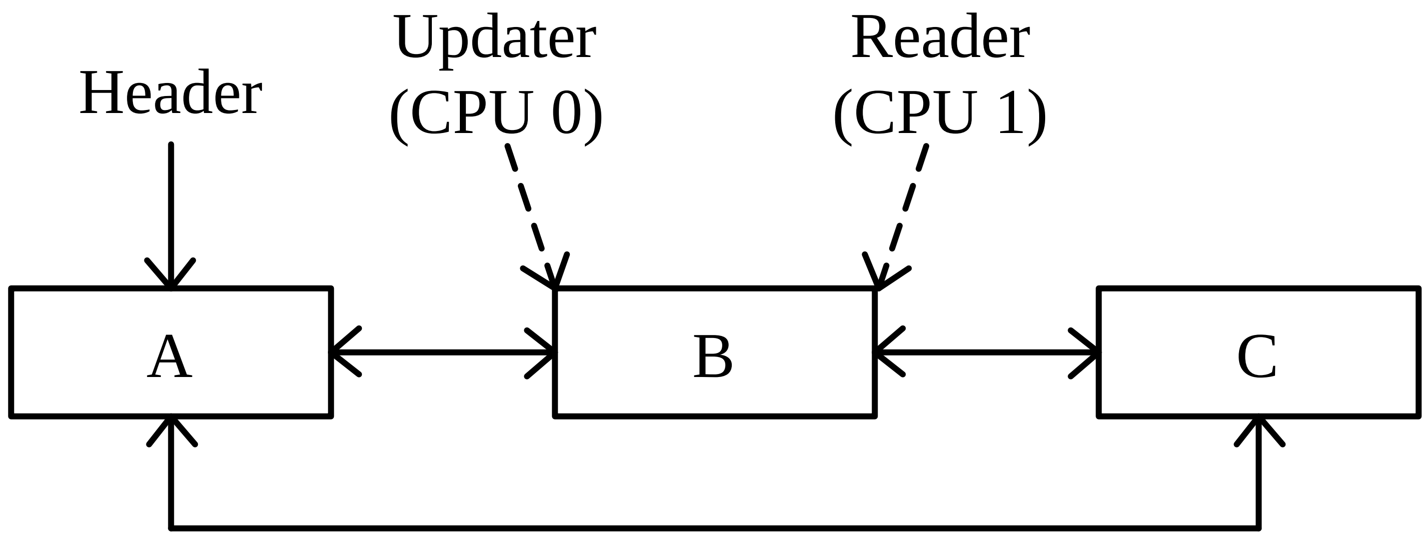
Grace Period

Phase 2

- Simple, straightline code
- Locking OK if read-mostly access
  - Faster designs available

Read-Copy Update Animation

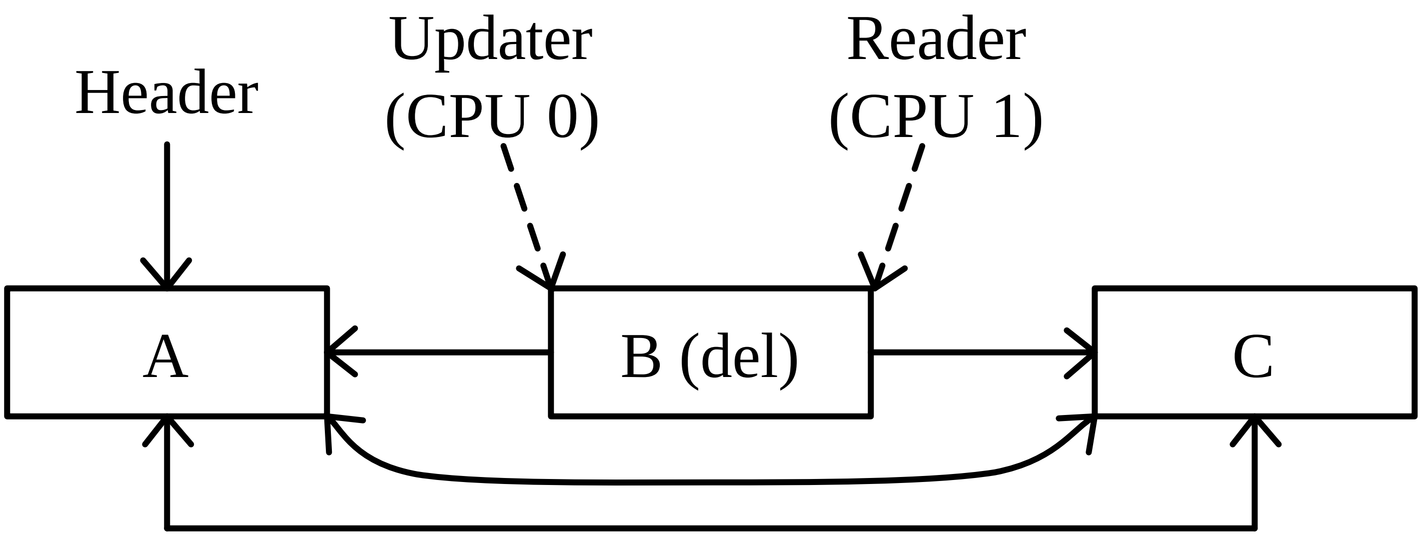
- Initial List State
  - Doubly linked list



Read-Copy Update Animation

- First Phase Complete:

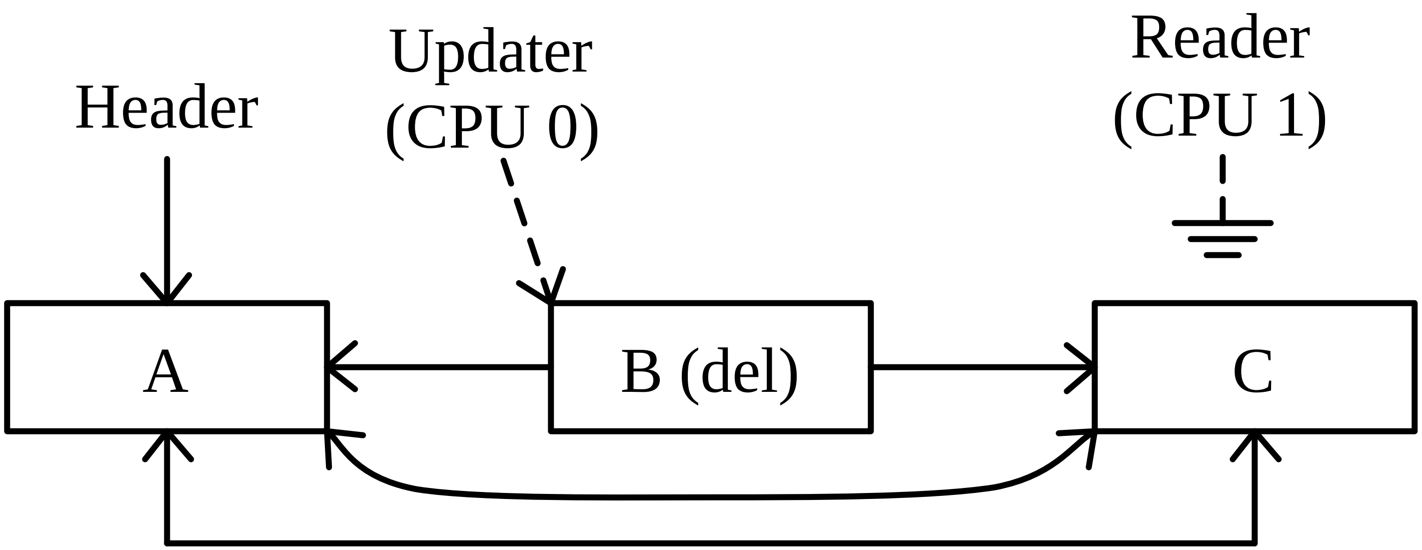
```
lock(&list_updater_lock);
p = prev->next;
prev->next = p->next;
unlock(&list_updater_lock);
```



Read-Copy Update Animation

- End of Grace Period

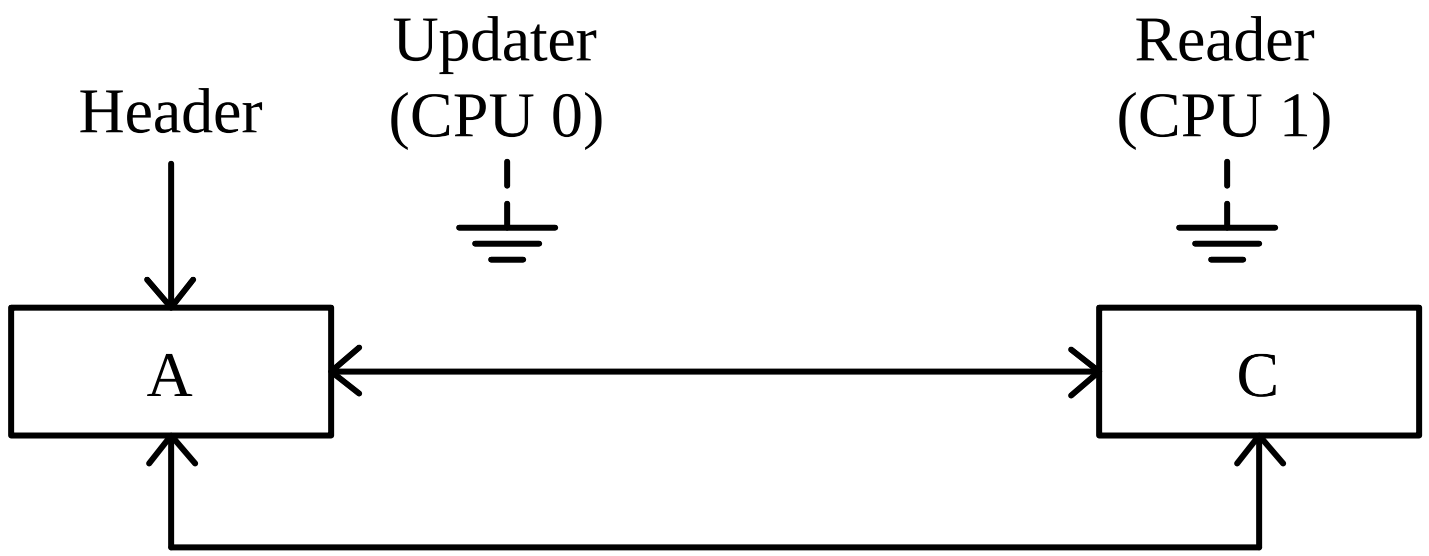
```
wait_for_rcu();
```



Read-Copy Update Animation

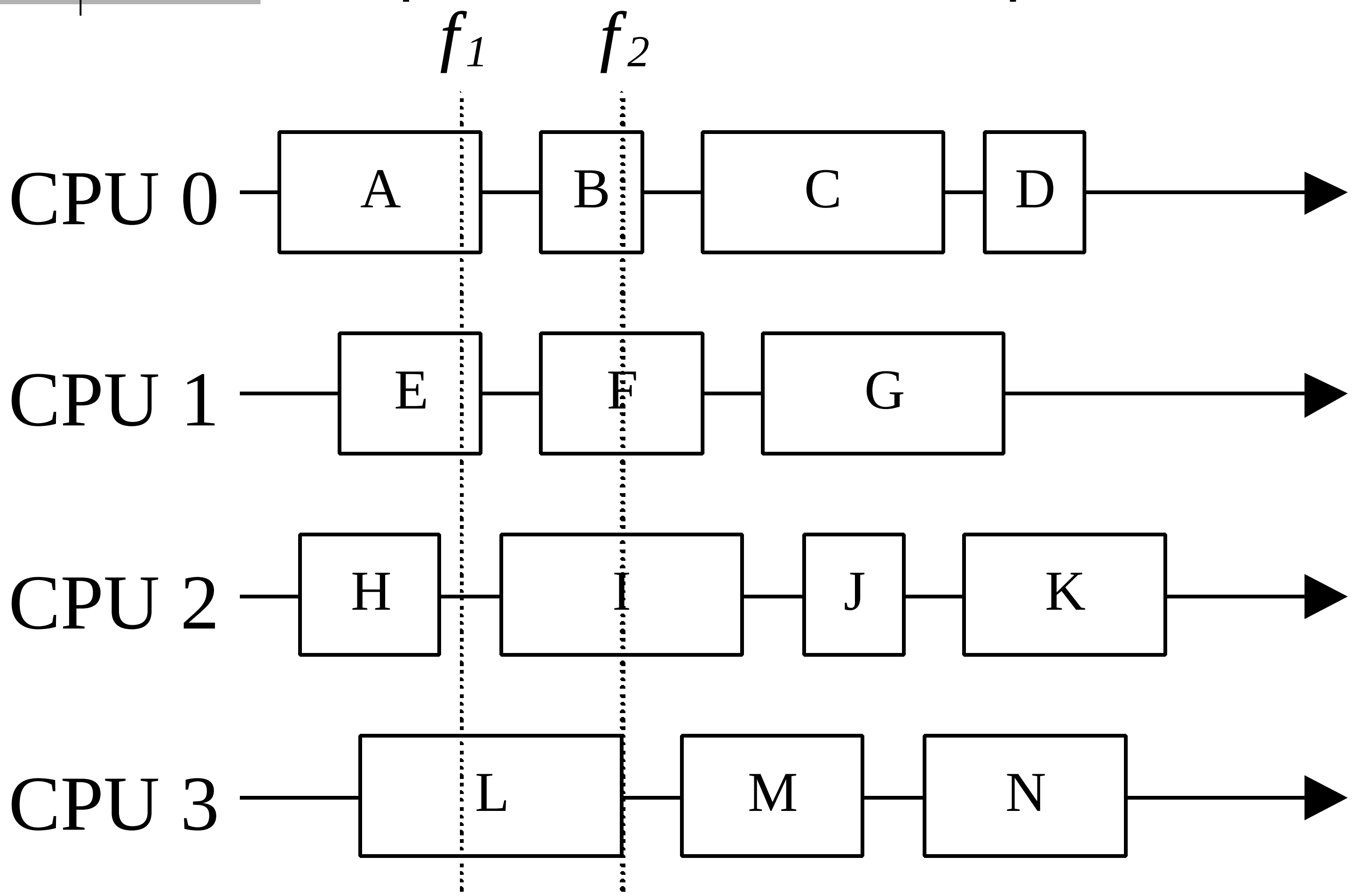
- Second Phase Complete

```
kfree(p);
```

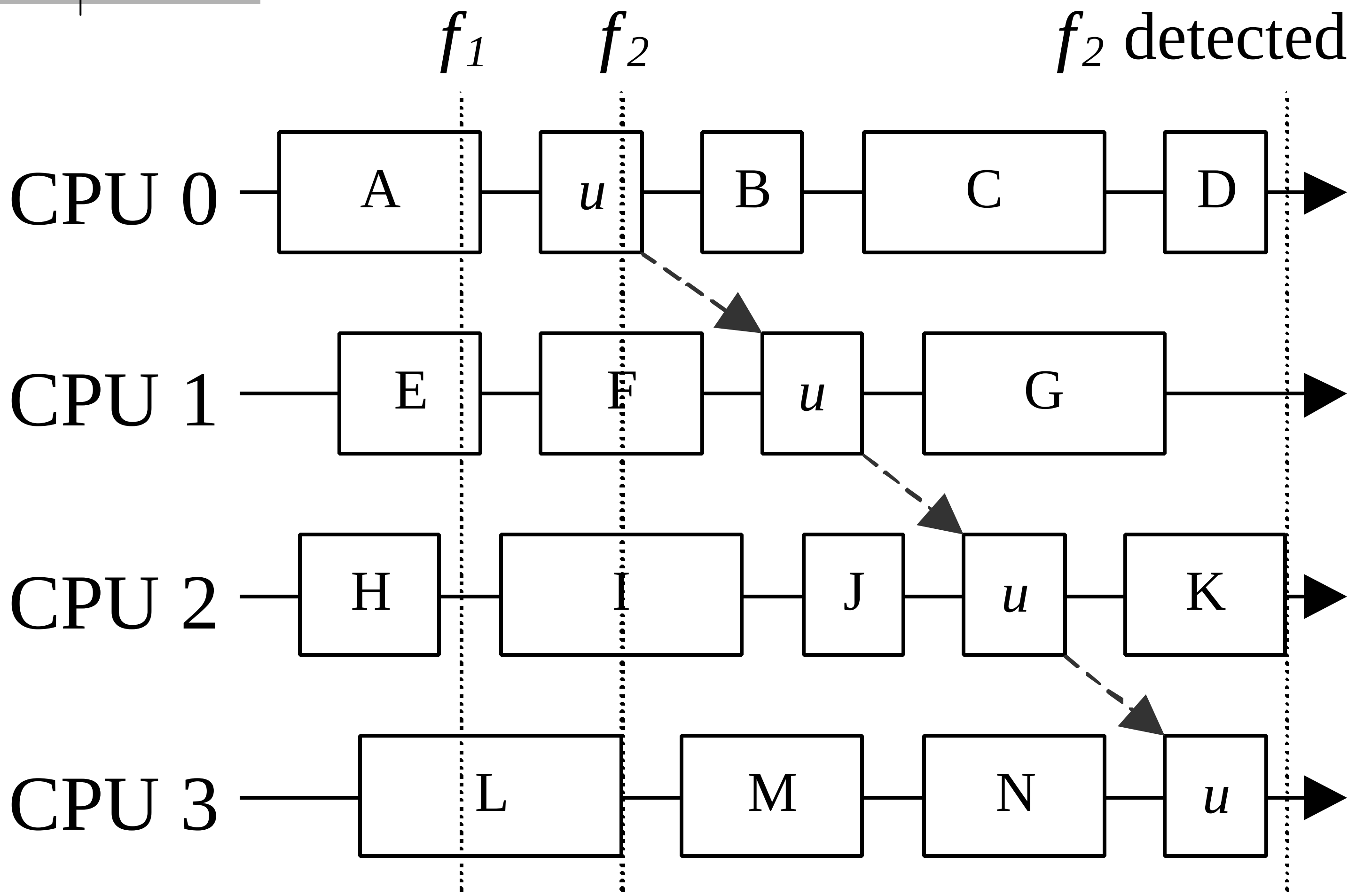


What is a Grace Period?

- Time after which all pre-existing operations have completed.



Detecting End of Grace Period



Code to Detect Grace Period

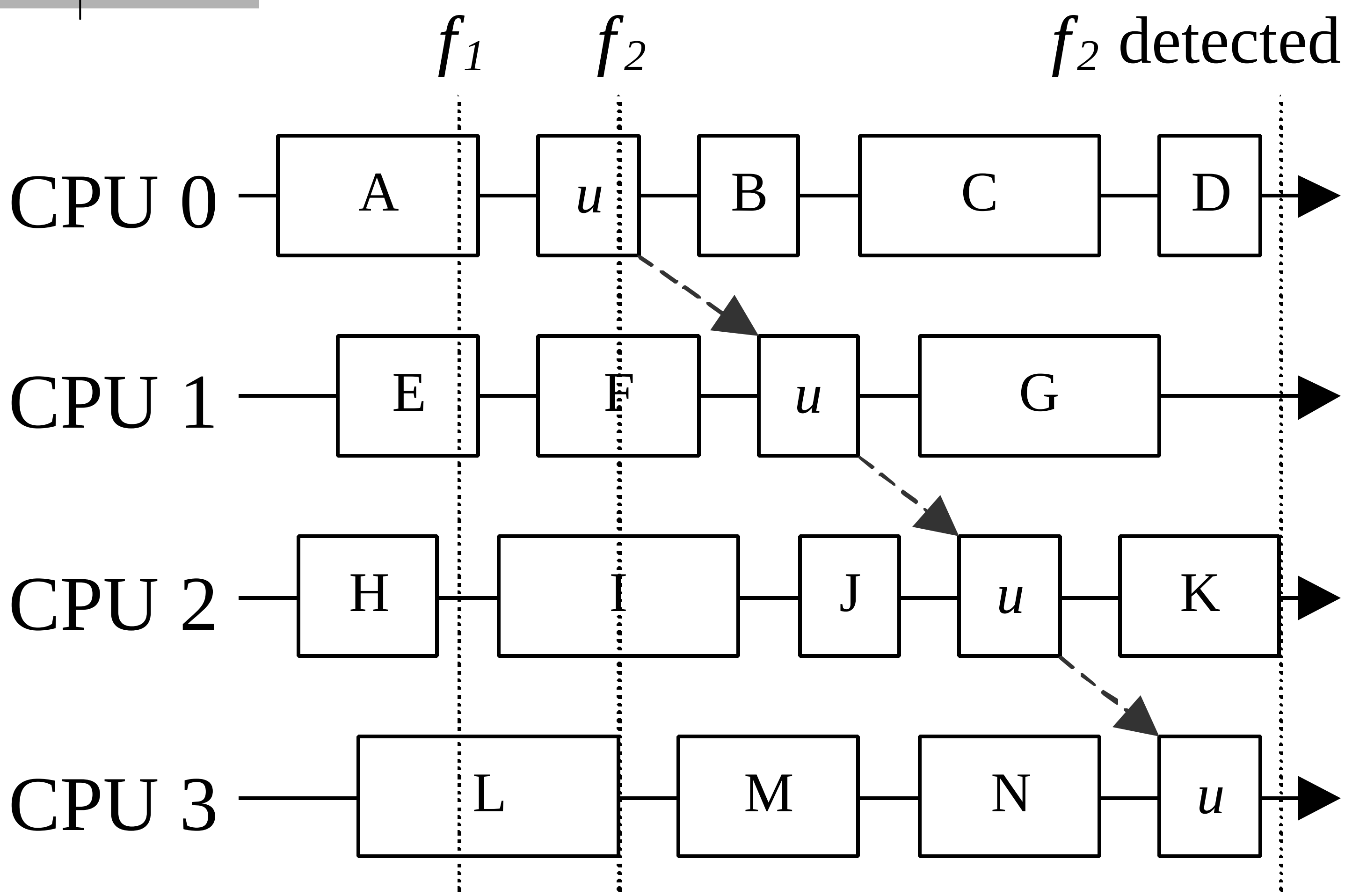
```
void wait_for_rcu()
{
   for (i = 0; i < n; i++) {
      run_on(i);
   }
}
```

- This simple implementation has some shortcomings: blocks caller, so:
  - Cannot be invoked from interrupt, with spinlock held, or with interrupts disabled
  - *Slooooow*:
    - Cannot "batch" requests for grace periods.
    - Multiple context switches per grace period: high overhead
    - Can be stalled indefinitely by real-time tasks (see paper)
    - Can throttle update rate

Overview

- Why is this goal important?
- How the $#@#!! can readers safely access a changing data structure without locking???
  - *Without writers needing a gazillion cycles to perform an update?*
- Does this really help in real-world code?

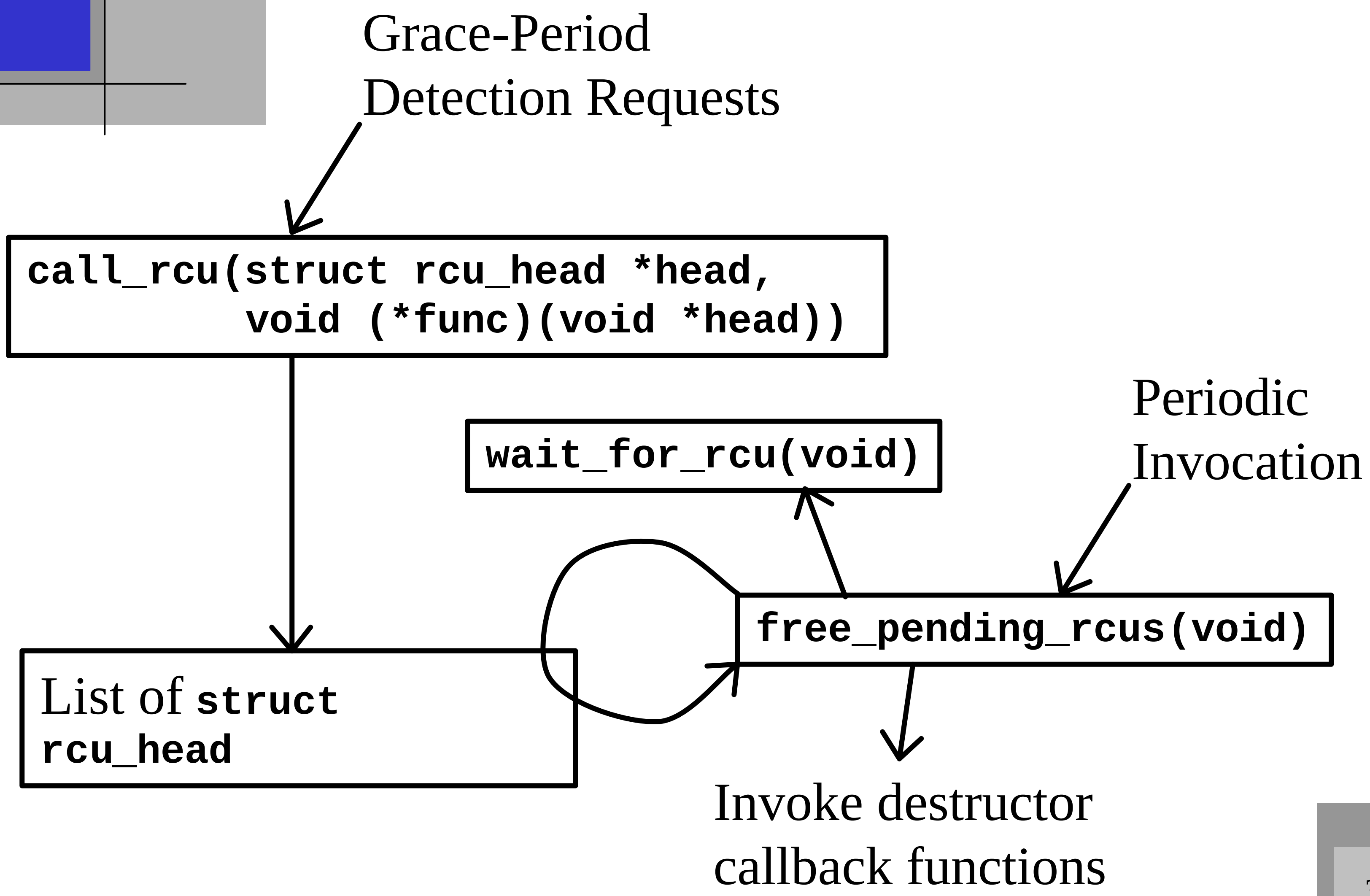
One Grace Period for All...



Amortized Grace Period

- Update code registers a callback
- Callbacks queued onto list
- Daemon periodically:
  - Removes all callbacks from list
  - Invokes wait_for_rcu()
  - Invokes all callbacks removed from list
- Allows batching, use from all execution contexts, and is *much* faster

Design to Detect Grace Period



Code to Detect Grace Period

```
struct rcu_head
{
   struct rcu_head *next;
   void (*func)(void *obj);
};
```

- The “next” pointer links the list together
- The “func” field is the destructor

Code to Detect Grace Period

```
void call_rcu(struct rcu_head *head,
              void (*func)(void *head))
{
   unsigned long flags;
   head->destructor = func;
   spin_lock_irqsave(&rcu_lock, flags);
   head->next = rcu_list;
   rcu_list = head;
   spin_unlock_irqrestore(&rcu_lock, flags);
}
```

- Can be called with locks held, from interrupt handler, with interrupts suppressed
- Also *much* faster
  - Still subject to cacheline bouncing…
- And we still need to clean up rcu_list…

Code to Clean Up rcu_list

```
void free_pending_rcus(void)
{
   struct rcu_head *list;
   unsigned long flags;
   spin_lock_irq(&rcu_lock, flags);
   list = rcu_list;
   rcu_list = NULL;
   spin_unlock_irq(&rcu_lock, flags);
   if (list) {
      wait_for_rcu();
      while (list) {
         struct rcu_head *next =
            list->next;
         list->destructor(list);
         list = next;
      }
   }
}
```

Read-Copy Update API

- wait_for_rcu(): Wait for a grace period.
- call_rcu(struct rcu_head *head, void (*func)(void *head)): Invoke the specified function at the end of a grace period.
- kmalloc_rcu(size_t size, in flags): kmalloc(), with with an rcu_head struct prepended.
- kfree_rcu(void*obj,void(*destructor)(void*)): kfree() after a grace period. Memory must be from kmalloc_rcu().

Read-Copy Update API

- vmalloc_rcu() & vfree_rcu(): ditto.
- For kmem_cache_alloc/_free(), use call_rcu() specifying destructor function.
- Related APIs
  - wmb(): Needed to make sure that writes are seen in order by other CPUs
    - Existing API
    - Some question about the Alpha implementation: Alpha's WMB instruction affects only the CPU that executes it...

Overview

- Why is this goal important?
- How the $#@#!! can readers safely access a changing data structure without locking???
  - Without writers needing a gazillion cycles to perform an update?
- *Does this really help in real-world code?*

Linux File Descriptor Management

```
if (i) {
   /* initialize new sets and bits */
}
nfds = xchg(&files->max_fdset, nfds);
new_openset = xchg(&files->open_fds,
                   new_openset);
new_execset = xchg(&files->close_on_exec,
                   new_execset);
write_unlock(&files->file_lock);
free_fdset(new_openset, nfds);
free_fdset(new_execset, nfds);
write_lock(&files->file_lock);
```

Original Code. read_lock() used to access.

Linux File Descriptor Management

```
if (i) {
   /* initialize new sets and bits */
}
wmb();
files->open_fds = new_openset;
files->close_on_exec = new_execset;
wmb();
files->max_fdset = nfds;
spin_unlock(&files->file_lock);
wait_for_rcu();
spin_lock(&files->file_lock);
free_fdset(old_openset, old_nfds);
free_fdset(old_execset, old_nfds);
```

Read-Copy Update, Slow Version. No locks to access!!!

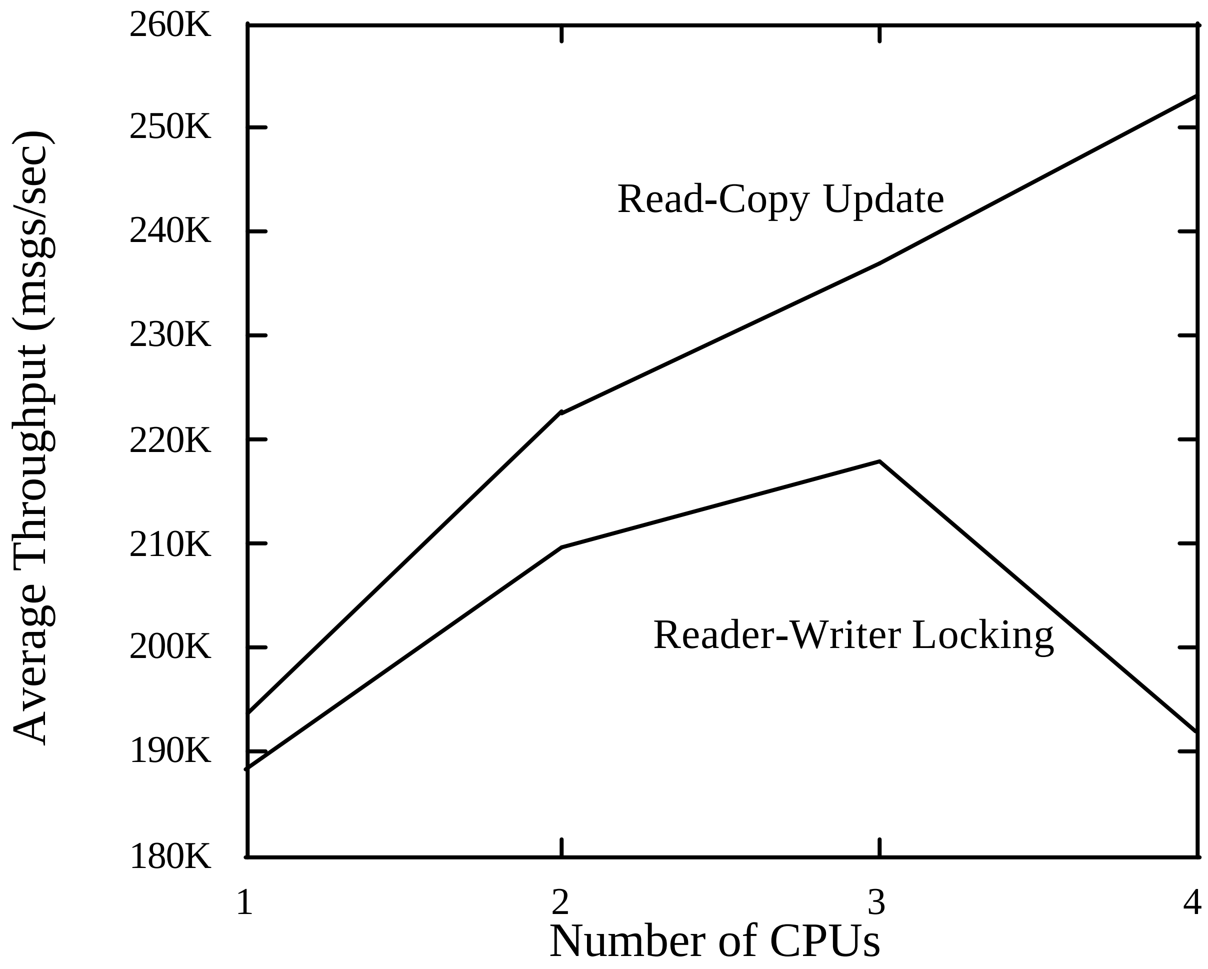
Linux File Descriptor Management

```
if (i) {
   /* initialize new sets and bits */
}
wmb();
files->open_fds = new_openset;
files->close_on_exec = new_execset;
wmb();
files->max_fdset = nfds;
free_fdset(old_openset, old_nfds);
free_fdset(old_execset, old_nfds);
```

kfree_rcu() instead of kfree()

Read-Copy Update, Fast Version. No locks to access!!!

Linux File Descriptor Management



"Chat" Benchmark (M. Soni: http://lse.sourceforge.net/locking/files_struct_rcu.txt)

Other uses in Linux

- Module unloading patch for 2.4 kernel
  - Correctly handle module uses that race with unloading that module
- Hotplug CPU patch for 2.4 kernel
  - Ensure that all other CPUs are aware outgoing CPU is leaving before it is fully removed
- See paper for more details

Known Uses

- DYNIX/ptx (since 1993)
- Tornado/K42 (pervasive)
- Patches to Linux:
  - Module unloading
  - File descriptor management
  - Hotplug CPU support

Related Work

- Garbage-collector-based grace period
  - Kung & Lehman, 1980
- Timeout-based grace period
  - Jacobson, 1993
- Read-copy update with grace period left as an exercise to the reader
  - Manber & Ladner, 1984; Pugh, 1990
- Wait-free synchronization
  - Herlihy, 1993

Future Work

- Look at simple but fast implementations
- Continue investigating application to Linux
- Investigate applicability to user-level software
  - Real-time databases and systems
  - Reactive systems
- Analysis at high contention levels
- Formal description and correctness proofs

Availability

- Read-copy update may be freely used under GPL.

Summary

- Read-copy update can reduce complexity while improving performance and scaling
  - Works *with* rather than *against* Moore's Law
- Key idea: break update into two phases:
  - Create updated version while leaving old version for ongoing operations (first phase)
  - Wait for a dynamically sized grace period
  - Do cleanup operations (second phase)

Conclusion

- Simple, high-performance and -scaling algorithms for read-mostly situations
  - Readers are *not* be required to acquire locks, execute atomic operations, or disable interrupts
    - Read-side code same as UP user-level implementation
    - Performance scales with CPU core clock rate, *not* with memory latency
  - Writers have to do a *little* more work
- Algorithms available for preemptive environments