1 Introduction

I presented an overview of read-copy update (RCU) \([22, 17, 11]\) at the May 2015 Dagstuhl workshop on Compositional Verification Methods for Next-Generation Concurrency, and was pleasantly but profoundly surprised to learn that a number of the formal-verification researchers in attendance were disappointed to have not seen any RCU code. This document is an attempt to give them some degree of satisfaction.

This document therefore illustrates a few simple examples of concurrent data structures, each of which has roughly similar counterparts in the Linux kernel. Each of these examples should be short enough to be compatible with formal-verification techniques, and is accompanied by an overview of the reasoning process that a kernel hacker might use when deciding whether or not a given example is applicable to the situation at hand.

To that end, Section 2 presents a warm-up exercise involving split counters, Section 3 shows a toy implementation of the RCU infrastructure, Section 4 gives an RCU implementation of bags, Section 5 overviews an RCU implementation of bags that is suitable for very large sets, and Section 6 overviews one kernel hacker’s view of RCU.

2 Warmup Exercise: Split Counters

Although RCU is conceptually quite simple, effective use of RCU often requires a subtle but profound change in thinking about concurrency. This document therefore starts not with RCU, but rather with a warmup exercise involving one of the simplest and most intuitive possible algorithms, namely that of integer addition, in the guise of the split counter. The semantics of a split counter are similar to those of an atomically manipulated single global counter, but with the addition of relaxed ordering semantics in conjunction with weakly ordered hardware and compilers.

The remainder of this section is organized as follows: Section 2.1 presents the implementation of a simple split counter, Section 2.2 gives an extreme elaboration of kernel-hacker thought process as to why this implementation is correct, Section 2.3 provides an error-injected version of the split-counter implementation for use in verifying verifiers, Section 2.4 lists the behaviors exhibited by split counters compared to an atomically manipulated global counter, and finally Section 2.5 gives the thought process that a kernel hacker might actually use when selecting split counters to solve a counting problem.

2.1 Split-Counter Implementation

Because the canonical implementation of split counters is trivial, this discussion will start with the implementation.

Split counters are implemented by providing a separate counter for each thread. To update the counter, a given thread updates its per-thread counter using simple relaxed loads and stores. To read out the value of the counter, all threads’ counters are accessed using relaxed loads, and the values loaded are summed.
1 DEFINE_SPLIT_COUNTER(mycount);
2
3 void add_split_counter(unsigned long v)
4 {
5     WRITE_ONCE(__get_thread_var(mycount),
6     READ_ONCE(__get_thread_var(mycount)) + v);
7 }
8
9 unsigned long read_split_counter(void)
10 {
11     int t;
12     unsigned long sum = 0;
13     for_each_thread(t)
14         sum += READ_ONCE(__get_thread_var(mycount));
15     return sum;
16 }

Figure 1: Split Counter

There is no use of any sort of memory-ordering con-
straints or of any sort of read-modify-write atomic
operations. These counters are bounded and exhibit
the same wrap-around behavior that is exhibited by a
simple C-language unsigned integer variable. Sample
code is shown in Figure 1. Note that $\text{READ}_\text{ONCE}()$
($\text{WRITE}_\text{ONCE}()$) can be thought of as a C11 memory
order relaxed load (respectively store) with volatile
semantics.\footnote{Within the Linux kernel, these primitives are implemented via casts to volatile.}

This trivial algorithm is used very heavily in ker-
nels and server applications in order to provide ex-
tremely lightweight gathering of important statistical
values, for but one example, the amount of network
data transmitted and received by the system.

2.2 Kernel-Hacker Split-Counter Cor-
rectness Argument

Split counters rely on the commutative and associa-
tive laws of modular addition. The effect of a split
counter is to form the following sum:

$$ S = \sum_{t \in T, 0 \leq i \leq N_t} A_{t,i} \quad (1) $$

Where $S$ is the desired sum, $T$ is the set of threads,
$N_t$ is the number of addition operations executed by
thread $t$, and $A_{t,i}$ is the value of thread $t$’s $i$th addition
operations.

The associative law of modular addition allows ar-
britary grouping of the addition operations. When
running on real hardware, a wise choice is to group
by thread, which is implemented using the per-thread
counters. These per-thread counters can then be
summed to arrive at the correct value of $S$. The com-
mutative law of addition further allows use of weak-
memory ordering, because the order of addition has
no effect on the sum.

However, this line of reasoning must face the addi-
tional challenge of summation operations proceeding
concurrently with addition operations. Bounds on
the sum are needed.

Rough bounds can be provided by a mythical
global counter that reflects the current aggregate
value of the split counter. This global counter might
take of the sequence of values that would be taken
on by an atomically manipulated global counter, but
the mythical status avoids the pathological levels of
memory contention that would be experienced by a
concrete implementation running on a large system.

Let $V$ be the set of values taken on by the mythical
counter during the execution of a given instance of
$\text{read_split_counter}()$. The the bounds on $S$ are
given by:

$$ \min V \leq S \leq \max V \quad (2) $$

Where $\min V$ is the value of the smallest element
of set $V$ and, similarly, $\max V$ is the value of the largest
element of $V$.

Exact bounds require knowing the maximum time
required for an update carried out by one CPU to
be visible by another. Vendors are unfortunately re-
luctant to release this information, but an estimate
could be derived empirically. Given such an estimate
$E$, set $V$ is collected over a time period starting $E$
before the start of a given instance of $\text{read_split_}
counter()$ and ending $E$ after that instance’s com-
pletion.

In practice, these bounds are sufficiently tight for
many use cases.
2.3 Potential Split-Counter Bugs

It is wise to maintain a healthy skepticism of a successful verification result. After all, a verification tool might simply unconditionally print \texttt{VERIFICATION SUCCESSFUL}. If this tool included code that did nothing in sufficiently complex ways, we might be none the wiser even after examining its source code. It is therefore also wise to run the alleged verification tool on a program that contains an intentional bug. Given that I have never observed a bug in a split-counters implementation in a quarter century of parallel programming, it is safe to assume that split counters is a trivial software system. The bugs introduced in Figure 2 will therefore likely seem to be somewhat contrived. However, contrived or not, a formal verification run that fails to find the bugs introduced by any of the \texttt{FORCE\_BUG\_*} C-preprocessor symbols must be viewed with some suspicion.

2.4 Split-Counter Behaviors

The behaviors of a split counter are those of an atomically updated global counter, but with the addition of weak-memory behaviors. For an example of weak-memory behavior, consider the following set of concurrent operations:

1. Thread 0: \texttt{add_split_counter(1)}
2. Thread 1: \texttt{add_split_counter(2)}
3. Thread 2: \texttt{r1 = read_split_counter()}
4. Thread 3: \texttt{r2 = read_split_counter()}

Given a global atomically manipulated counter, the following outcomes are allowed:

1. \texttt{r1 == 0 \&\& r2 == 0}
2. \texttt{r1 == 0 \&\& r2 == 1}
3. \texttt{r1 == 0 \&\& r2 == 2}
4. \texttt{r1 == 0 \&\& r2 == 3}
5. \texttt{r1 == 1 \&\& r2 == 0}
6. \texttt{r1 == 1 \&\& r2 == 1}
7. \texttt{r1 == 1 \&\& r2 == 3}
8. \texttt{r1 == 2 \&\& r2 == 0}
9. \texttt{r1 == 2 \&\& r2 == 2}
10. \texttt{r1 == 2 \&\& r2 == 3}
11. \texttt{r1 == 3 \&\& r2 == 0}
12. \texttt{r1 == 3 \&\& r2 == 1}
13. \texttt{r1 == 3 \&\& r2 == 2}
14. \( r_1 == 3 \&\& r_2 == 3 \)

Split counters allow the following outcomes in addition to those listed above:

1. \( r_1 == 1 \&\& r_2 == 2 \)
2. \( r_1 == 2 \&\& r_2 == 1 \)

The challenge is thus to construct a formal specification of split counters, verify a correct implementation, and locate bugs in erroneous implementations, as exemplified by those in Figure 2.

2.5 How Kernel Hackers Really Model Split Counters

The actual thought process is extremely simple: A split counter is a mechanism with extremely lightweight updates and approximate reads, where the approximation is many orders of magnitude more than good enough for the intended use cases. There is therefore absolutely no need to do any sort of error analysis in practice. It would typically take less time for the kernel hacker to decide whether or not to use a split counter than it took you to read this paragraph. Actually implementing the split counter would take a similar amount of time.

A counter update is expected to have roughly the same performance characteristics as that of a simple addition operation on a private variable, possibly with an additional small constant cost to compute the location of the running thread’s per-thread counter. Reading out the aggregate value of the counter is expected to take up to \( N - 1 \) additions and to incur up to \( 2N - 2 \) cache misses, where \( N \) is the number of threads. One might instead expect \( N - 1 \) cache misses, but that fails to account for the cache misses incurred by each other thread the next time it attempts to update its per-thread counter.

Please note that this split-counter is merely the simplest member of a large set of concurrent counter algorithms[13, Chapter 5]. The more complex members pose less trivial verification challenges.

3 RCU Infrastructure

There is a surprisingly large number of independent inventions of mechanisms vaguely resembling RCU [10, 24, 7, 23, 8, 9, 4, 22, 6, 25]. The distinctive feature of RCU in the Linux kernel is the fact that a large number of developers has successfully used it. Recently, there has also been a surprisingly large number of proofs of correctness (both formal and informal of RCU algorithms and implementations [1, 5, 26]. That said, these proofs focus on RCU’s safety properties, leaving much unsaid about RCU’s ordering properties. The rest of this section therefore fills in this gap.

This section uses very imprecise terminology to denote ordering properties. More precise determination of the ordering properties is left as an exercise for the reader. This is typical when kernel hacking: The kernel hacker does not care what ordering a given algorithm exhibits in any formal sense, but rather whether or not it is strong enough to do the job at hand.

3.1 Toy Implementation of RCU Infrastructure

Figure 3 shows a “toy” implementation of a fragment of the RCU API for a non-preemptive environment. This implementation provides full read-side performance, but suffers from a number of problems:

1. It has abysmal update-side scalability and energy efficiency.
2. The prohibition against blocking while in RCU read-side critical sections degrades real-time response.
3. Updaters can degrade real-time response for readers (or, alternatively, high-priority readers can starve updaters).

\[\text{There is rumored to be an additional Czech-language dissertation proving correctness of RCU, but I do not have a citation.}\]

\[\text{The full implementation has many tens of API members [15].}\]
4. Updaters can fail in the presence of CPU-hotplug operations.

That said, this implementation has the advantage of abject simplicity. In addition, an early implementation of RCU within the DYNIX/ptx clusters implementation used an approach quite similar to this.

The \texttt{rcu\_read\_lock()} and \texttt{rcu\_read\_unlock()} primitives on lines 1 and 2 of the figure generate no code and in fact don’t even reach the compiler backend. The purpose of these primitives is not to affect machine state, but rather to remind the developer of the need to avoid blocking within the resulting RCU read-side critical section.

The \texttt{rcu\_dereference()} primitives on lines 3-8 of the figure simply applies volatile semantics to the load \cite{3}.

In conjunction with suitable restrictions on use of the returned value \cite{21}, these volatile semantics ensure that any dereferences of the pointer returned from \texttt{rcu\_dereference()} will be ordered after the \texttt{rcu\_dereference()} itself.

The \texttt{rcu\_assign\_pointer()} primitive on lines 9-13 of the figure is slightly weaker than a \texttt{memory\_order\_release()} store. (Recent versions of the Linux kernel actually use a \texttt{memory\_order\_release()} store.)

\footnote{\texttt{READ\_ONCE()} is the new name for read-side use cases of the \texttt{ACCESS\_ONCE()} primitive described in this document.}
The pointer-access primitive `rcu_dereference()` has semantics similar to a C11 memory order consume load. Roughly speaking, subsequent operations whose address or data depends on the value returned by `rcu_dereference()` will be ordered after the `rcu_dereference()`. A more precise definition of these ordering semantics is work in progress within the C and C++ standards committees.

### 3.3 RCU Grace Periods Are Strongly Ordered

If any portion of any RCU read-side critical section causally precedes a given RCU grace period, then the entirety of that RCU read-side critical section causally precedes any code that causally follows that same RCU grace period. Similarly, if any portion of any RCU read-side critical section causally follows a given RCU grace period, then the entirety of that RCU read-side critical section causally follows any code that causally precedes that same RCU grace period. If no part of a given RCU read-side critical section causally follows or causally precedes a given grace period, then there is no guarantee of ordering against any other RCU read-side critical section with respect to that grace period. Roughly speaking, causal ordering is defined to be the union of modification order, reads-from, from-reads, and program order.

Figure 6 shows an example of this ordering. If `r1==0`, we know that line 6 of `t0()`’s RCU read-side critical section causally precedes `t1()`’s grace period. Therefore, we know that both lines 6 and 7 causally precede line 15, implying that `r2==0`. On the other hand, if `r2==1`, we know that line 7 of `t0()`’s RCU read-side critical section causally follows `t1()`’s grace period. Therefore, we know that both lines 6 and 7 causally follow line 13, implying that `r1==1`. The outcome `r1==0&\&r2==1` is therefore excluded.

In contrast, if all of Figure 6’s loads and stores were memory order seq_cst, and if the `synchronize_rcu()` on line 14 were omitted, all four possible outcomes would be allowed.

The ordering provided by the combination of RCU read-side critical sections and RCU grace periods is thus extremely strong, and this ordering has proven to be extremely useful in practice.
Figure 7: Bag Implemented Using RCU-Protected Linked List

Figure 7 shows a possibly buggy implementation of a bag (which permits duplicates) using an RCU-protected linked list. Such an implementation might be useful when:

1. The bag is to be queried far more frequently than it is to be modified.
2. The integers in the bag might be quite large, ruling out use of small arrays of counters.
3. The number of elements in the bag will be quite small, so that the overhead of traversing the linked list is negligible.

Of course, very similar code implements mappings, bags, and ordered sets, but let’s keep things simple.

4 RCU Bag

Lines 1-4 show the data structure representing an element in this bag, which contains a pair of pointers for insertion into a circular doubly linked list and an integer representing the value of the element. Line 5 represents the head of the list, which is also a pair of pointers. Line 6 defines the spinlock that guards modification of this list, initially in unlocked state.

Lines 9-20 show the membership-query function. Line 12 enters an RCU read-side critical section, and lines 15 and 18 exit it. Line 13 iterates over the list headed by the `mybag` global variable, and for each element executes the code on lines 14-17. If line 14 determines that the current element matches the desired key, line 15 exits the RCU read-side critical section, and line 16 returns 1 to indicate that the specified value is a member of the bag. Otherwise, control eventually reaches line 18, which exits the RCU read-side critical section, allowing line 19 to return 0 to indicate that the specified value is not a member of the bag.

Lines 22-34 show the member-addition function. Line 26 allocates a new `elem` structure, and lines 27-28 return 0 if allocation fails. Line 29 sets the key field of the new element to the given key. Line 30 enters the RCU read-side critical section, and lines 33 and 36 exit it. Line 31 inserts the new element into the list, and line 39 returns 1.

4.1 Bag Implementation

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In this case, the grace period completely overlaps the given RCU read-side critical section.

Kudos to Jade Alglave for calling attention to the strong ordering characteristics of RCU grace periods.
and 28 handle the out-of-memory case. Line 29 initializes the element’s key. Line 30 acquires the lock, line 31 does the pointer manipulations required to add the new member to the bag along with any needed memory-ordering constraints, and line 32 releases the lock. Finally, line 33 returns 1 to indicate success.

Lines 36-51 show the member-removal function. This is similar to member(), but substitutes locking on lines 40, 44, and 49 for the RCU operations on lines 12, 15, and 18. Because we hold the lock, there can of course be no concurrent updates to the linked list. Once an element is found, line 43 does the linked-list manipulations required to remove the element, line 44 releases the lock, and line 45 waits for an RCU grace period to elapse. Once control reaches line 46, there can no longer be any readers holding a reference to the newly deleted element, so line 46 can safely free it.

This represents a straightforward concurrent implementation of a bag, with excellent read-side performance and scalability.

Candidate bug injections include omitting the synchronize_rcu(), prematurely terminating the loops in member() and remove(), randomly refusing to add the element, randomly perturbing the key, and so on.

4.2 Bag Memory-Ordering Properties

The insertions and removals will be fully ordered, courtesy of mybaglock. Interestingly enough, if there are additions but no removals, membership queries will be strongly ordered, as illustrated by Figure 8. The key point is that the list pointers are subject to coherence properties similar to those of C11 memory_order_relaxed accesses. Therefore, if element 0 was added to the list before element 1, if t3() sees element 1 on line 19, it must also see element 0 on line 20. The opposite insertion order imposes the corresponding constraint of t2(). Therefore, the IRIW cycle is forbidden.

In short, sequential consistency (or something very similar to it) has been restored at the linked-list level for additions and membership queries, despite RCU’s extremely weak read-side ordering properties.

4.3 RCU Bag Timing

In the absence of updates, readers incur no cache misses, and on average incur a number of loads that increases linearly with the number of elements in the bag. This data structure is therefore quite suitable for situations where the bag has few elements and updates are rare. In contrast, frequent updates will of course result in excessive contention on mybaglock, and will further inflict cache misses on all readers.

5 RCU Large Bag

If a bag has a large number of members, the linked-list implementation discussed in Section 4 will of course suffer from poor performance due to a linear search through a linked list. One time-honored solution to this problem is to use a hash table, as shown in

```c
1 void t0(void)
2 { 
3   add(0);
4 }
5
6 void t1(void)
7 { 
8   add(1);
9 }
10
11 void t2(void)
12 { 
13   r1 = member(0);
14   r2 = member(1);
15 }
16
17 void t3(void)
18 { 
19   r1 = member(1);
20   r2 = member(0);
21 }
```

Figure 8: RCU Bags Strongly Ordered For Addition
1 struct elem {
2   struct list_head *list;
3   int key;
4 };  
5 struct bucket {
6   struct list_head *head;
7   spinlock_t lock
8 };  
9 struct bucket mybag[NBUCKETS];
10
11 int member(int key)
12 {  
13   struct elem *ep;
14   int idx = hash(key);
15   rcu_read_lock();
16   list_for_each_entry_rcu(ep, &mybag[idx].head, list)
17     if (ep->key == key) {
18       rcu_read_unlock();
19       return 1;
20     }
21   rcu_read_unlock();
22   return 0;
23 }
24
25 int add(int key)
26 {  
27   struct elem *ep;
28   int idx = hash(key);
29   ep = kmalloc(sizeof(*ep), GFP_KERNEL);
30   if (!ep)
31     return 0;
32   ep->key = key;
33   spin_lock(&mybag[idx].lock);
34   list_add_rcu(ep, &mybag[idx].head);
35   spin_unlock(&mybag[idx].lock);
36   return 1;
37 }
38
39 int remove(int key)
40 {  
41   struct elem *ep;
42   int idx = hash(key);
43   ep = kmalloc(sizeof(*ep), GFP_KERNEL);
44   if (!ep)
45     return 0;
46   ep->key = key;
47   spin_lock(&mybag[idx].lock);
48   list_for_each_entry_rcu(ep, &mybag[idx].head, list)
49     if (ep->key == key) {
50       list_del_rcu(ep);
51       spin_unlock(&mybag[idx].lock);
52       synchronize_rcu();
53       kfree(ep);
54       return 1;
55     }
56     spin_unlock(&mybag[idx].lock);
57   return 0;
58 }
59
60 Figure 9: Bag Implemented Using RCU-Protected Hash Table

Figure 9. The code is quite similar to that in Figure 7, with the differences being the use of a hash function hash() to select one of NBUCKETS linked lists instead of using a single linked list. Note also that global locking has been replaced by per-bucket locking.

Of course, the need to select a hash-table size at compile time can be quite inconvenient, however, implementation of RCU-protected resizable hash tables is reasonably straightforward [28, 27, 20]. Two of these variants may be found in the Linux kernel. An overview of one of the simpler implementations is also available [13, Chapter 10].

The memory-ordering litmus test shown in Figure 8 also applies to the hash-table implementation. However, the coherence property no longer holds because there is now more than one list header. The hash-table implementation can therefore produce the counter-intuitive outcome r1==1&&r2==0&&r3==1&&r4==0, so that the strong ordering restored at the linked-list level is lost at the hash-table level.

That said, most Linux-kernel use cases of bags have very weak ordering requirements, which in turn means that the typical Linux kernel hacker will likely consider any discussion of ordering properties to be a pointless distraction.

The bug-injection candidates are similar to those called out in Section 4.1, with the addition of bugs involving inconsistent hash functions for different operations.

The timing of each bucket of this RCU hash-table bag is similar to that of the linked-list version, although of course the hash-table bag can tolerate higher update rates, at least assuming that the updates spread nicely across the hash table. Depending on the size of the hash table, the level of memory pressure, and the frequency of updates, it might or might not be wise to cache-align the elements of the mybag array.

6 Kernel-Hacker View of RCU

RCU is rarely used by itself, but instead in conjunction with other synchronization techniques, with a variety of combinations used to achieve a wide range
of synchronization goals [11, 18, 19, 13]. For example, RCU can be used in conjunction with locking to implement an atomic move of elements from one binary search tree to another, which can be generalized to other types of linked structures [14, 12, 16]. This in turn means that it is not sufficient to merely understand RCU. It is instead necessary to understand RCU usage patterns that involve combinations of other synchronization primitives. For but one example, the Linux kernel’s mechanism for traversing filesystem directory hierarchies uses a combination of locking, reference counting, sequence locking, and RCU. Enumerating the full space of such combinations is beyond the scope of this paper, although some information may be found elsewhere [13, Chapters 9 and 13]. The remainder of this section focuses on RCU timing (Section 6.1), RCU semantics (Section 6.2), and RCU applicability (Section 6.3).

6.1 RCU Timing

RCU’s read-side primitives are exceedingly fast and scalable. In the limiting case of a server-class Linux kernel build, `rcu_read_lock()` and `rcu_read_unlock()` are zero cost, as can be seen in Figure 3. Other implementations require non-atomic updates to per-thread variables, often with no ordering constraints. However, real-time Linux-kernel implementations that do priority boosting on RCU readers will require invoking the scheduler in order to do deboosting at `rcu_read_unlock()` time. However, if a given RCU reader is running at the highest possible priority level, it will not be preempted, and will therefore not be priority boosted. Therefore, RCU readers running at the highest priority level enjoy full read-side performance.

The `rcu_dereference()` primitive applies volatile semantics, and thus might result in a slight decrease in performance due to suppression of certain types of compiler optimizations. In addition, on DEC Alpha, `rcu_dereference()` incurs the overhead of a full memory barrier. However, on current commodity hardware, `rcu_dereference()` has overhead roughly that of an unordered load instruction. The overheads of `rcu_read_lock()`, `rcu_read_unlock()`, and `rcu_dereference()` have been empirically shown to be constant with the number of CPUs up to 1024 CPUs on a Power server.

The `rcu_assign_pointer()` primitive applies volatile release semantics, which can inflict measurable overhead on RCU updaters. However, this overhead is negligible compared to the latency and overhead of `synchronize_rcu()`. In the Linux kernel, `synchronize_rcu()` has a latency of at least several milliseconds, and sometimes triggers warnings that are emitted if an RCU grace period lasts longer than 21 seconds. The CPU overhead of a given grace period is substantial, consuming microseconds on small systems and potentially even hundreds of microseconds on thousand-CPU systems. However, the Linux kernel uses batching, so that a given grace period might be shared by more than a thousand RCU updaters, reducing the per-update CPU overhead to negligible levels.

6.2 RCU Semantics

The two fundamental guarantees of RCU are the publish-subscribe guarantee linking `rcu_assign_pointer()` with `rcu_dereference()`, and the grace-period guarantee linking `synchronize_rcu()` with `rcu_read_lock()` and `rcu_read_unlock()` [5]. The grace-period guarantee can be stated in two ways: (1) The `synchronize_rcu()` primitive waits for all pre-existing RCU readers, and (2) If a task has executed a given `rcu_read_lock()` and accesses a given RCU-protected resource, some property $P$ of that resource will be preserved until that task reaches the corresponding `rcu_read_unlock()`.

Here are some properties that RCU is used to preserve:

1. Existence.
2. Identity.
3. Type safety.
4. System state.

Each property is discussed in one of the following sections.
1 int go_undercover(int key)
2 {
3 struct elem *ep;
4 int idx = hash(key);
5 spin_lock(&mybag[idx].lock);
6 list_for_each_entry_rcu(ep, &mybag[idx].head, list)
7 if (ep->key == key) {
8 list_del_rcu(ep);
9 spin_unlock(&mybag[idx].lock);
10 synchronize_rcu();
11 ep->key = -ep->key;
12 idx = hash(ep->key);
13 spin_lock(&mybag[idx].lock);
14 list_add_rcu(ep, &mybag[idx].head);
15 spin_unlock(&mybag[idx].lock);
16 return 1;
17 }
18 spin_unlock(&mybag[idx].lock);
19 return 0;
20 }

Figure 10: RCU-Protected Hash Table Bag Identity Change

6.2.1 RCU Existence Guarantees

Existence is the property preserved in the RCU-protected bags discussed in Sections 4 and 5. Updates preserve this property by interposing an RCU grace period between the time that the resource is rendered inaccessible to readers and the time that the resource is reclaimed (in this case, freed).

Reliance on existence guarantees is illustrated by lines 17-19 of `add()` in Figure 9. Any element traversed by `list_for_each_entry_rcu()` must remain in existence (that is, cannot be freed) until after control reaches one of the `rcu_read_unlock()` calls on either line 19 or 22. This existence guarantee ensures that the `->key` access on line 18 remains meaningful, even in the face of concurrent removals.

If a guarantee is to be relied on, something somewhere must provide that guarantee, and in this case the provider is lines 49-52 of `remove()` in Figure 9. Line 49 renders the element inaccessible to readers, but the element is not passed to `kfree()` (line 52) until after an RCU grace period has elapsed (line 51).

6.2.2 RCU Identity Guarantees

In some cases, a resource is not destroyed, but rather its identity is changed. For example, consider the function `go_undercover()` shown in Figure 10. Rather than freeing the element, as is done by `remove()`, lines 12-16 negate the element’s key and then add it back into the bag. This code is therefore not providing an existence guarantee, but rather an identity guarantee.

Readers can rely on this guarantee in exactly the same way that they rely on existence guarantees.

6.2.3 RCU Type-Safety Guarantees

There are several situations in the Linux kernel where lightweight readers are needed, but where the overhead and latency of RCU grace periods cannot be tolerated. The `SLAB_DESTROY_BY_RCU` slab-allocator flag is used for this purpose, which allows an immediate free operation, but which guarantees that the type of the object will not change until the reader exits its RCU read-side critical section. However, the identity of the object can change at any time, so readers must carry out identity checks, usually after acquiring a lock or reference count associated with the object. These identity checks often rely on subtle global invariants.

6.2.4 RCU System-State Guarantees

A trivial form of system-state guarantee is illustrated by the code in Figure 11. The system must periodically undergo servicing, during which time normal operations can still be carried out, but alternative implementations of those operations must be used. For example, during servicing, `do_something_carefully()` must be invoked instead of the usual `do_something()`.

This transition to servicing state is mediated by the variable `state`, which can take on the three values called out on lines 1-3, but which is initially `STATE_NORMAL`, courtesy of the C language’s default initialization to zero.

The `do_something_service()` function on lines 7-18 enters an RCU read-side critical section, then on line 12 takes a snapshot of the global `state` variable. Line 13 checks for normal state, which results in a call to `do_something()`, otherwise, `do_something_carefully()` is called. This code clearly needs a
#define STATE_NORMAL 0
#define STATE_WANT_SERVICE 1
#define STATE_SERVICING 2

int state;

void do_something_service(void)
{
    int state_snap;

    rcu_read_lock();
    state_snap = READ_ONCE(state);
    if (state_snap == STATE_NORMAL)
        do_something();
    else
        do_something_carefully();
    rcu_read_unlock();
}

void start_service(void)
{
    WRITE_ONCE(state, STATE_WANT_SERVICE);
    synchronize_rcu();
    WRITE_ONCE(state, STATE_SERVICING);
}

Figure 11: RCU-Mediated System-State Change

system-state guarantee: If line 13 determines that the state is STATE_NORMAL, then the state cannot change to STATE_SERVICING until after do_something() returns.

This system-state guarantee is provided by the start_service() function shown on lines 20-25. Line 22 sets state to STATE_WANT_SERVICE, and then line 23 waits for an RCU grace period to elapse. By the time control passes to line 24, all RCU readers that might have called do_something() have completed, so it is safe to set state to STATE_SERVICING.

This system-state guarantee was one of the first uses of RCU within Sequent’s DYNIX/ptx clustering product [22, 17].

6.3 RCU Applicability

RCU can provide excellent performance and scalability, but it does so via specialization. As illustrated in the upper blue box in Figure 12, RCU is best suited to workloads that are read-mostly in cases where RCU’s clients do not require consistent data. In such cases, use of RCU means simply adding RCU “annotations” similar to those shown in the RCU-protected bag implementations in Sections 4 and 5. The net result is excellent performance and ease of use.

RCU can also be used for read-mostly workloads where RCU’s clients require consistent data, as indicated by the green box. One way to achieve this is to include a lock and a ->deleted flag in each data element. When rendering the element inaccessible to readers, the updater acquires the per-element lock, renders the element inaccessible to readers, sets the flag, releases the lock, and then continues as before. Readers acquire the per-element lock and check the flag. If the flag is set, they release the lock and continue as if they had not found the element. Otherwise, if the flag is clear, they release the lock and proceed normally. This technique was applied to the Linux kernel’s System-V IPC subsystem [2].

This same technique works for read-write workloads where RCU’s clients require consistent data, as indicated by the yellow box. The same per-element lock and flag may be used, but the performance and perhaps also the scalability will likely be somewhat degraded.

Finally, as indicated by the red box, RCU is unlikely to be well-suited to write-mostly workloads where RCU’s clients require consistent data. However, a couple of exceptions have been found thus far. In the first exception, RCU takes on the same role that garbage collectors do for certain types of non-blocking synchronization algorithms. In the second exception, a real-time workload has tight response-time constraints for a few infrequently executed code
paths that include RCU readers, while the code paths containing RCU updates, though perhaps frequently executed, are not subject to response-time constraints.

7 Summary

This paper has illustrated a few simple examples of concurrent data structures, each of which has roughly similar counterparts in the Linux kernel. Each of these examples should be small enough to be compatible with formal-verification techniques, and is accompanied by timing information as well as an overview of the reasoning process that a kernel hacker might use when deciding whether or not a given example is applicable to the situation at hand.

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References


