What is RCU, Fundamentally?

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This article was contributed by Paul McKenney

[*Editor's note: this is the first in a three-part series on how the read-copy-update mechanism works. Many thanks to Paul McKenney and Jonathan Walpole for allowing us to publish these articles. The remaining two sections will appear in future weeks.*]

Part 1 of 3 of **What is RCU, Really?**

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Introduction

Read–copy update (RCU) is a synchronization mechanism that was added to the Linux kernel in October of 2002. RCU achieves scalability improvements by allowing reads to occur concurrently with updates. In contrast with conventional locking primitives that ensure mutual exclusion among concurrent threads regardless of whether they be readers or updaters, or with reader–writer locks that allow concurrent reads but not in the presence of updates, RCU supports concurrency between a single updater and multiple readers. RCU ensures that reads are coherent by maintaining multiple versions of objects and ensuring that they are not freed up until all pre–existing read–side critical sections complete. RCU defines and uses efficient and scalable mechanisms for publishing and reading new versions of an object, and also for deferring the collection of old versions. These mechanisms distribute the work among read and update paths in such a way

as to make read paths extremely fast. In some cases (non-preemptable kernels), RCU's read-side primitives have zero overhead.

Quick Quiz 1: But doesn't seqlock also permit readers and updaters to get work done concurrently?

This leads to the question "what exactly is RCU?", and perhaps also to the question "how can RCU *possibly* work?" (or, not infrequently, the assertion that RCU cannot possibly work). This document addresses these questions from a fundamental viewpoint; later installments look at them from usage and from API viewpoints. This last installment also includes a list of references.

RCU is made up of three fundamental mechanisms, the first being used for insertion, the second being used for deletion, and the third being used to allow readers to tolerate concurrent

insertions and deletions. These mechanisms are described in the following sections, which focus on applying RCU to linked lists:

1. Publish–Subscribe Mechanism (for insertion)
2. Wait For Pre–Existing RCU Readers to Complete (for deletion)
3. Maintain Multiple Versions of Recently Updated Objects (for readers)

These sections are followed by concluding remarks and the answers to the Quick Quizzes.

Publish–Subscribe Mechanism

One key attribute of RCU is the ability to safely scan data, even though that data is being modified concurrently. To provide this ability for concurrent insertion, RCU uses what can be thought of as a publish–subscribe mechanism. For example, consider an initially `NULL` global pointer `gp` that is to be modified to point to a

newly allocated and initialized data structure. The following code fragment (with the addition of appropriate locking) might be used for this purpose:

```
 1 struct foo {
 2   int a;
 3   int b;
 4   int c;
 5 };
 6 struct foo *gp = NULL;
 7
 8 /* . . . */
 9
10 p = kmalloc(sizeof(*p), GFP_KERNEL);
11 p->a = 1;
12 p->b = 2;
13 p->c = 3;
14 gp = p;
```

Unfortunately, there is nothing forcing the compiler and CPU to execute the last four assignment statements in order. If the assignment to `gp` happens before the initialization of `p`'s fields, then concurrent readers could see the uninitialized values. Memory barriers are required to keep things ordered, but memory barriers are notoriously difficult to use. We therefore encapsulate

them into a primitive `rcu_assign_pointer()` that has publication semantics. The last four lines would then be as follows:

```
1 p->a = 1;
2 p->b = 2;
3 p->c = 3;
4 rcu_assign_pointer(gp, p);
```

The `rcu_assign_pointer()` would *publish* the new structure, forcing both the compiler and the CPU to execute the assignment to `gp` *after* the assignments to the fields referenced by `p`.

However, it is not sufficient to only enforce ordering at the updater, as the reader must enforce proper ordering as well. Consider for example the following code fragment:

```
1 p = gp;
2 if (p != NULL) {
3   do_something_with(p->a, p->b, p->c);
4 }
```

Although this code fragment might well seem immune to misordering, unfortunately, the DEC Alpha CPU [PDF] and value-speculation compiler optimizations can, believe it or not, cause

the values of `p->a`, `p->b`, and `p->c` to be fetched before the value of `p`! This is perhaps easiest to see in the case of value-speculation compiler optimizations, where the compiler guesses the value of `p`, fetches `p->a`, `p->b`, and `p->c`, then fetches the actual value of `p` in order to check whether its guess was correct. This sort of optimization is quite aggressive, perhaps insanely so, but does actually occur in the context of profile-driven optimization.

Clearly, we need to prevent this sort of skullduggery on the part of both the compiler and the CPU. The `rcu_dereference()` primitive uses whatever memory-barrier instructions and compiler directives are required for this purpose:

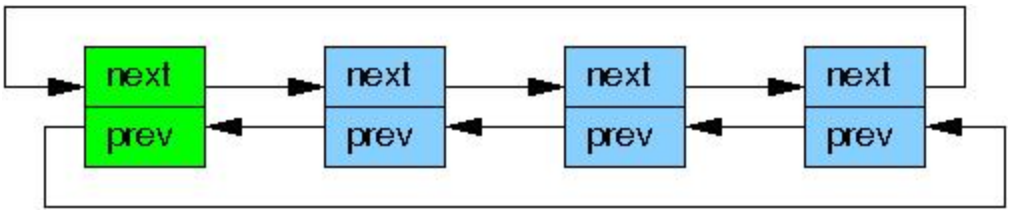
```
1 rcu_read_lock();
2 p = rcu_dereference(gp);
3 if (p != NULL) {
4   do_something_with(p->a, p->b, p->c);
5 }
6 rcu_read_unlock();
```

The `rcu_dereference()` primitive can thus be thought of as *subscribing* to a given value of the specified pointer, guaranteeing that subsequent dereference operations will see any initialization that occurred before the corresponding publish (`rcu_assign_pointer()`) operation.

The `rcu_read_lock()` and `rcu_read_unlock()` calls are absolutely required: they define the extent of the RCU read-side critical section. Their purpose is explained in the next section, however, they never spin or block, nor do they prevent the `list_add_rcu()` from executing concurrently. In fact, in non-`CONFIG_PREEMPT` kernels, they generate absolutely no code.

Although `rcu_assign_pointer()` and `rcu_dereference()` can in theory be used to construct any conceivable RCU-protected data structure, in practice it is often better to use higher-level constructs. Therefore, the `rcu_assign_pointer()` and `rcu_dereference()` primitives have been

embedded in special RCU variants of Linux's list-manipulation API. Linux has two variants of doubly linked list, the circular `struct list_head` and the linear `struct hlist_head`/`struct hlist_node` pair. The former is laid out as follows, where the green boxes represent the list header and the blue boxes represent the elements in the list.



Adapting the pointer-publish example for the linked list gives the following:

```
 1 struct foo {
 2   struct list_head list;
 3   int a;
 4   int b;
 5   int c;
 6 };
 7 LIST_HEAD(head);
 8
 9 /* . . . */
10
11 p = kmalloc(sizeof(*p), GFP_KERNEL);
```

```
12 p->a = 1;
13 p->b = 2;
14 p->c = 3;
15 list_add_rcu(&p->list, &head);
```

Line 15 must be protected by some synchronization mechanism (most commonly some sort of lock) to prevent multiple `list_add()` instances from executing concurrently. However, such synchronization does not prevent this `list_add()` from executing concurrently with RCU readers.

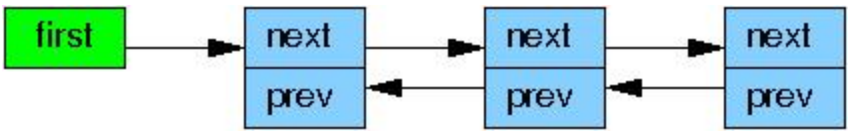
Subscribing to an RCU-protected list is straightforward:

```
1 rcu_read_lock();
2 list_for_each_entry_rcu(p, head, list) {
3   do_something_with(p->a, p->b, p->c);
4 }
5 rcu_read_unlock();
```

The `list_add_rcu()` primitive publishes an entry into the specified list, guaranteeing that the corresponding `list_for_each_entry_rcu()` invocation will properly subscribe to this same entry.

Quick Quiz 2: What prevents the `list_for_each_entry_rcu()` from getting a segfault if it happens to execute at exactly the same time as the `list_add_rcu()`?

Linux's other doubly linked list, the hlist, is a linear list, which means that it needs only one pointer for the header rather than the two required for the circular list. Thus, use of hlist can halve the memory consumption for the hash-bucket arrays of large hash tables.



Publishing a new element to an RCU-protected hlist is quite similar to doing so for the circular list:

```
1 struct foo {
2   struct hlist_node *list;
3   int a;
4   int b;
5   int c;
6 };
7 HLIST_HEAD(head);
```

```
 8
 9 /* . . . */
10
11 p = kmalloc(sizeof(*p), GFP_KERNEL);
12 p->a = 1;
13 p->b = 2;
14 p->c = 3;
15 hlist_add_head_rcu(&p->list, &head);
```

As before, line 15 must be protected by some sort of synchronization mechanism, for example, a lock.

Subscribing to an RCU-protected hlist is also similar to the circular list:

```
1 rcu_read_lock();
2 hlist_for_each_entry_rcu(p, q, head, list) {
3   do_something_with(p->a, p->b, p->c);
4 }
5 rcu_read_unlock();
```

Quick Quiz 3: Why do we need to pass two pointers into `hlist_for_each_entry_rcu()` when only one is needed for `list_for_each_entry_rcu()`?

The set of RCU publish and subscribe primitives are shown in the following table, along with additional primitives to "unpublish", or retract:

Category	Publish	Retract	Subscribe
Pointers	`rcu_assign_pointer()`	`rcu_assign_pointer(..., NULL)`	`rcu_dereference()`

Lists	`list_add_rcu()`
	`list_add_tail_rcu()`
	`list_replace_rcu()`
		`list_del_rcu()`	`list_for_each_entry_rcu()`

Hlists	`hlist_add_after_rcu()`
	`hlist_add_before_rcu()`
	`hlist_add_head_rcu()`
	`hlist_replace_rcu()`
		`hlist_del_rcu()`	`hlist_for_each_entry_rcu()`

Note that the `list_replace_rcu()`, `list_del_rcu()`, `hlist_replace_rcu()`, and `hlist_del_rcu()` APIs add a complication. When is it safe to free up the data element that was replaced or removed? In particular, how can we possibly know when all the readers have released their references to that data element?

These questions are addressed in the following section.

Wait For Pre-Existing RCU Readers to Complete

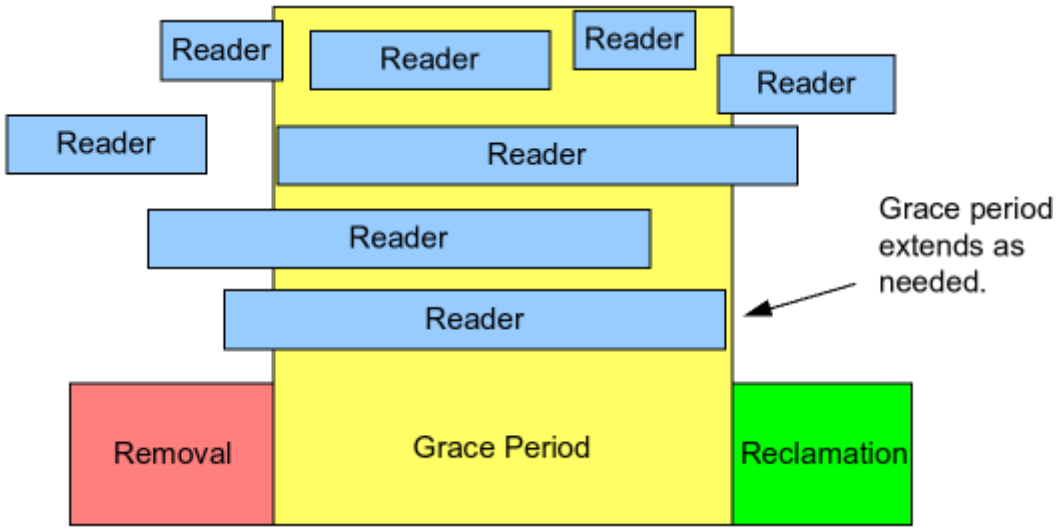
In its most basic form, RCU is a way of waiting for things to finish. Of course, there are a great many other ways of waiting for things to finish, including reference counts, reader-writer locks, events, and so on. The great advantage of RCU is that it can wait for each of (say) 20,000 different things without having to explicitly track each and every one of them, and without having to worry about the performance degradation, scalability limitations, complex deadlock scenarios, and memory-leak hazards that are inherent in schemes using explicit tracking.

In RCU's case, the things waited on are called "RCU read-side critical sections". An RCU read-side critical section starts with an `rcu_read_lock()` primitive, and ends with a corresponding `rcu_read_unlock()` primitive. RCU read-side critical

sections can be nested, and may contain pretty much any code, as long as that code does not explicitly block or sleep (although a special form of RCU called "SRCU" does permit general sleeping in SRCU read-side critical sections). If you abide by these conventions, you can use RCU to wait for *any* desired piece of code to complete.

RCU accomplishes this feat by indirectly determining when these other things have finished, as has been described elsewhere for RCU Classic and realtime RCU.

In particular, as shown in the following figure, RCU is a way of waiting for pre-existing RCU read-side critical sections to completely finish, including memory operations executed by those critical sections.



However, note that RCU read-side critical sections that begin after the beginning of a given grace period can and will extend beyond the end of that grace period.

The following pseudocode shows the basic form of algorithms that use RCU to wait for readers:

1. Make a change, for example, replace an element in a linked list.
2. Wait for all pre-existing RCU read-side critical sections to completely finish (for example, by using the `synchronize_rcu()` primitive). The key observation here is

that subsequent RCU read-side critical sections have no way to gain a reference to the newly removed element.

3. Clean up, for example, free the element that was replaced above.

The following code fragment, adapted from those in the previous section, demonstrates this process, with field a being the search key:

```
 1 struct foo {
 2   struct list_head list;
 3   int a;
 4   int b;
 5   int c;
 6 };
 7 LIST_HEAD(head);
 8
 9 /* . . . */
10
11 p = search(head, key);
12 if (p == NULL) {
13   /* Take appropriate action, unlock, and return. */
14 }
15 q = kmalloc(sizeof(*p), GFP_KERNEL);
16 *q = *p;
17 q->b = 2;
```

```
18 q->c = 3;
19 list_replace_rcu(&p->list, &q->list);
20 synchronize_rcu();
21 kfree(p);
```

Lines 19, 20, and 21 implement the three steps called out above. Lines 16–19 gives RCU ("read–copy update") its name: while permitting concurrent *reads*, line 16 *copies* and lines 17–19 do an *update*.

The `synchronize_rcu()` primitive might seem a bit mysterious at first. After all, it must wait for all RCU read–side critical sections to complete, and, as we saw earlier, the `rcu_read_lock()` and `rcu_read_unlock()` primitives that delimit RCU read–side critical sections don't even generate any code in non–`CONFIG_PREEMPT`kernels!

There is a trick, and the trick is that RCU Classic read–side critical sections delimited by `rcu_read_lock()` and `rcu_read_unlock()` are not permitted to block

or sleep. Therefore, when a given CPU executes a context switch, we are guaranteed that any prior RCU read-side critical sections will have completed. This means that as soon as each CPU has executed at least one context switch, *all* prior RCU read-side critical sections are guaranteed to have completed, meaning that `synchronize_rcu()` can safely return.

Thus, RCU Classic's `synchronize_rcu()` can conceptually be as simple as the following:

```
1 for_each_online_cpu(cpu)
2   run_on(cpu);
```

Here, `run_on()` switches the current thread to the specified CPU, which forces a context switch on that CPU.

The `for_each_online_cpu()` loop therefore forces a context switch on each CPU, thereby guaranteeing that all prior RCU read-side critical sections have completed, as required. Although this simple approach works for kernels in which preemption is

disabled across RCU read-side critical sections, in other words, for non-`CONFIG_PREEMPT` and `CONFIG_PREEMPT` kernels, it does *not* work for `CONFIG_PREEMPT_RT` realtime (-rt) kernels. Therefore, realtime RCU uses a different approach based loosely on reference counters.

Of course, the actual implementation in the Linux kernel is much more complex, as it is required to handle interrupts, NMIs, CPU hotplug, and other hazards of production-capable kernels, but while also maintaining good performance and scalability. Realtime implementations of RCU must additionally help provide good realtime response, which rules out implementations (like the simple two-liner above) that rely on disabling preemption.

Although it is good to know that there is a simple conceptual implementation of `synchronize_rcu()`, other questions remain. For example, what exactly do RCU readers see when traversing a

concurrently updated list? This question is addressed in the following section.

Maintain Multiple Versions of Recently Updated Objects

This section demonstrates how RCU maintains multiple versions of lists to accommodate synchronization–free readers. Two examples are presented showing how an element that might be referenced by a given reader must remain intact while that reader remains in its RCU read–side critical section. The first example demonstrates deletion of a list element, and the second example demonstrates replacement of an element.

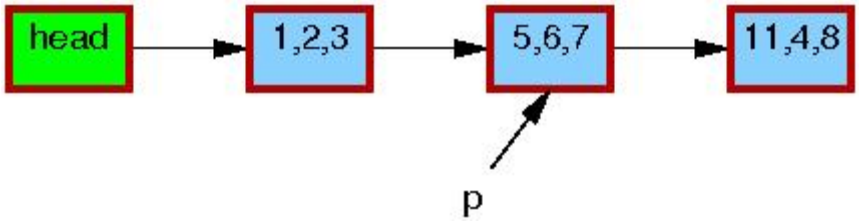
Example 1: Maintaining Multiple Versions During Deletion

To start the "deletion" example, we will modify lines 11–21 in the example in the previous section as follows:

```
1 p = search(head, key);
2 if (p != NULL) {
3   list_del_rcu(&p->list);
```

```
4   synchronize_rcu();
5   kfree(p);
6 }
```

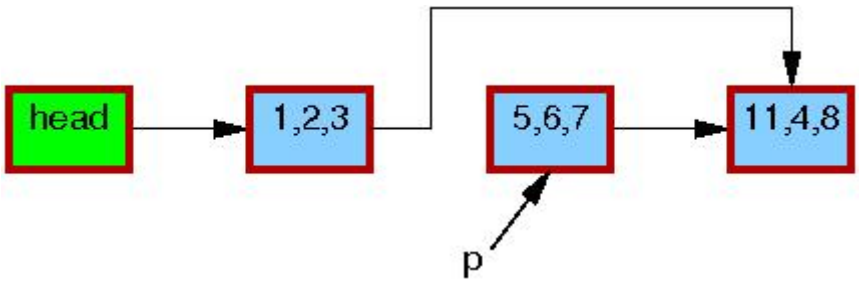
The initial state of the list, including the pointer `p`, is as follows.



The triples in each element represent the values of fields `a`, `b`, and `c`, respectively. The red borders on each element indicate that readers might be holding references to them, and because readers do not synchronize directly with updaters, readers might run concurrently with this entire replacement process. Please note that we have omitted the backwards pointers and the link from the tail of the list to the head for clarity.

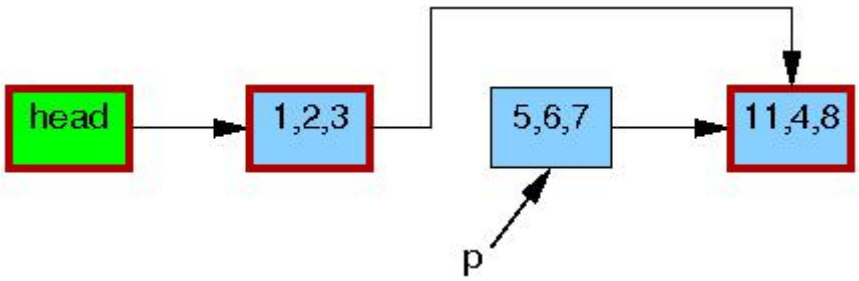
After the `list_del_rcu()` on line 3 has completed, the `5,6,7` element has been removed from the list, as shown below. Since readers do not synchronize directly with updaters,

readers might be concurrently scanning this list. These concurrent readers might or might not see the newly removed element, depending on timing. However, readers that were delayed (e.g., due to interrupts, ECC memory errors, or, in `CONFIG_PREEMPT_RT` kernels, preemption) just after fetching a pointer to the newly removed element might see the old version of the list for quite some time after the removal. Therefore, we now have two versions of the list, one with element `5,6,7` and one without. The border of the `5,6,7` element is still red, indicating that readers might be referencing it.



Please note that readers are not permitted to maintain references to element `5,6,7` after exiting from their RCU read-side critical sections. Therefore, once the `synchronize_rcu()` on line 4

completes, so that all pre-existing readers are guaranteed to have completed, there can be no more readers referencing this element, as indicated by its black border below. We are thus back to a single version of the list.



At this point, the 5,6,7 element may safely be freed, as shown below:

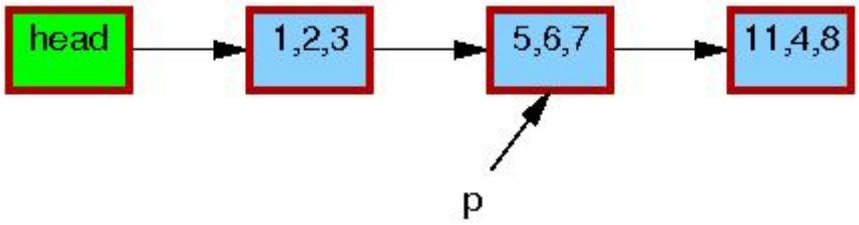
At this point, we have completed the deletion of element 5,6,7. The following section covers replacement.

Example 2: Maintaining Multiple Versions During Replacement

To start the replacement example, here are the last few lines of the example in the previous section:

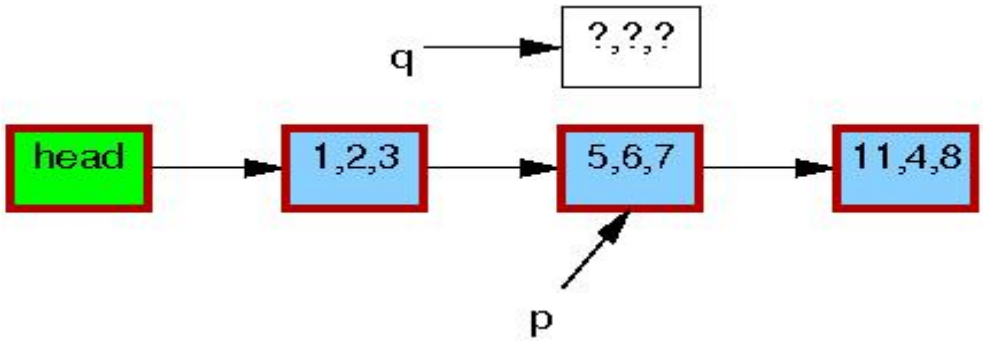
```
1 q = kmalloc(sizeof(*p), GFP_KERNEL);
2 *q = *p;
3 q->b = 2;
4 q->c = 3;
5 list_replace_rcu(&p->list, &q->list);
6 synchronize_rcu();
7 kfree(p);
```

The initial state of the list, including the pointer `p`, is the same as for the deletion example:

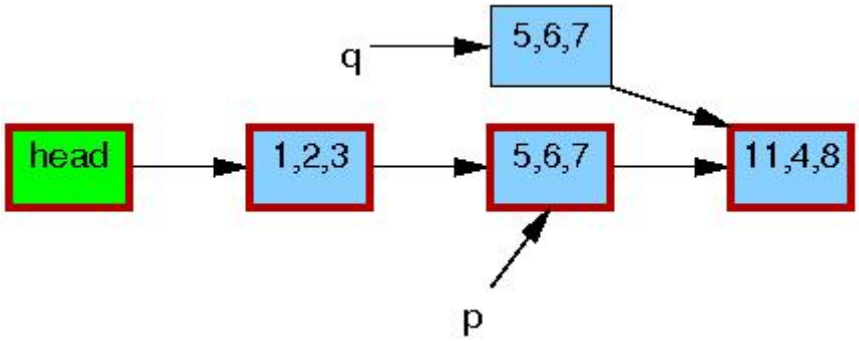


As before, the triples in each element represent the values of fields `a`, `b`, and `c`, respectively. The red borders on each element indicate that readers might be holding references to them, and because readers do not synchronize directly with updaters, readers might run concurrently with this entire replacement process. Please note that we again omit the backwards pointers and the link from the tail of the list to the head for clarity.

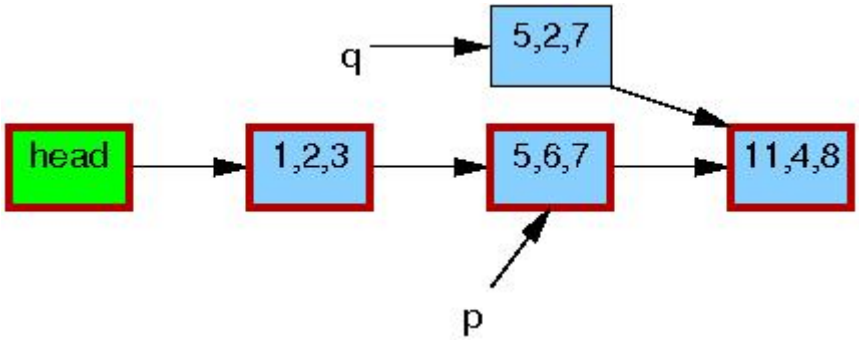
Line 1 `kmalloc()`s a replacement element, as follows:



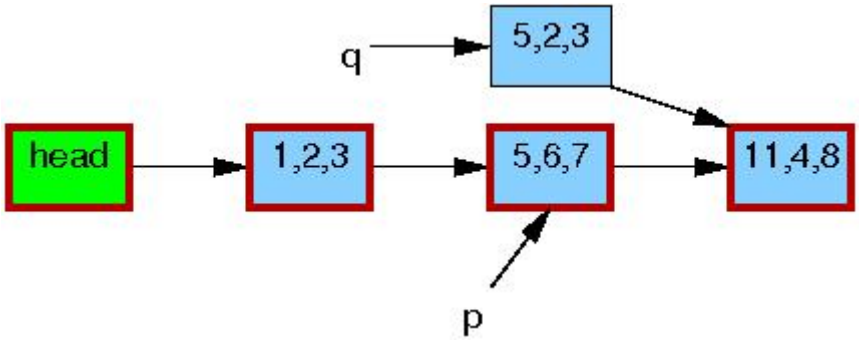
Line 2 copies the old element to the new one:



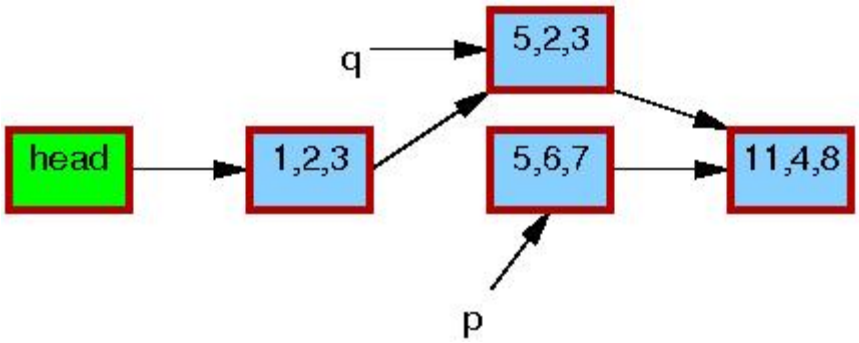
Line 3 updates `q->b` to the value "2":



Line 4 updates `q->c` to the value "3":

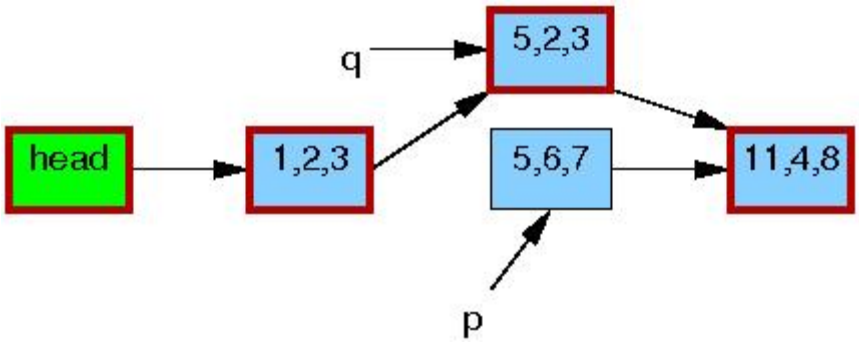


Now, line 5 does the replacement, so that the new element is finally visible to readers. At this point, as shown below, we have two versions of the list. Pre-existing readers might see the `5,6,7` element, but new readers will instead see the `5,2,3` element. But any given reader is guaranteed to see some well-defined list.

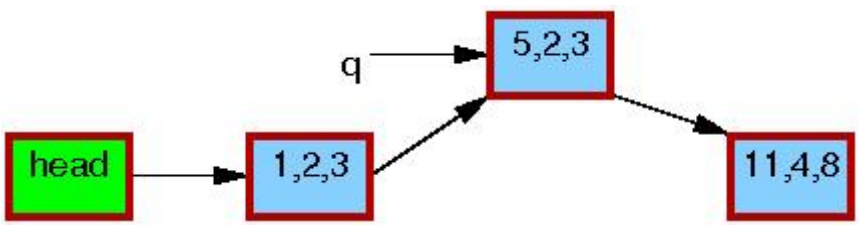


After the `synchronize_rcu()` on line 6 returns, a grace period will have elapsed, and so all reads that started before the `list_replace_rcu()` will have completed. In particular, any

readers that might have been holding references to the `5,6,7` element are guaranteed to have exited their RCU read–side critical sections, and are thus prohibited from continuing to hold a reference. Therefore, there can no longer be any readers holding references to the old element, as indicated by the thin black border around the `5,6,7` element below. As far as the readers are concerned, we are back to having a single version of the list, but with the new element in place of the old.



After the `kfree()` on line 7 completes, the list will appear as follows:



Despite the fact that RCU was named after the replacement case, the vast majority of RCU usage within the Linux kernel relies on the simple deletion case shown in the previous section.

Discussion

These examples assumed that a mutex was held across the entire update operation, which would mean that there could be at most two versions of the list active at a given time.

Quick Quiz 4: How would you modify the deletion example to permit more than two versions of the list to be active?

Quick Quiz 5: How many RCU versions of a given list can be active at any given time?

This sequence of events shows how RCU updates use multiple versions to safely carry out changes in presence of concurrent readers. Of course, some algorithms cannot gracefully handle

multiple versions. There are techniques [PDF] for adapting such algorithms to RCU, but these are beyond the scope of this article.

Conclusion

This article has described the three fundamental components of RCU-based algorithms:

1. a publish-subscribe mechanism for adding new data,
2. a way of waiting for pre-existing RCU readers to finish, and
3. a discipline of maintaining multiple versions to permit change without harming or unduly delaying concurrent RCU readers.

Quick Quiz 6: How can RCU updaters possibly delay RCU readers, given that the `rcu_read_lock()` and `rcu_read_unlock()` primitives neither spin nor block?

These three RCU components allow data to be updated in face of concurrent readers, and can be combined in different ways to implement a surprising variety of different types of RCU-based algorithms, some of which will be the topic of the next installment in this "What is RCU, Really?" series.

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Answers to Quick Quizzes

Quick Quiz 1: But doesn't seqlock also permit readers and updaters to get work done concurrently?

Answer: Yes and no. Although seqlock readers can run concurrently with seqlock writers, whenever this happens, the `read_seqretry()` primitive will force the reader to retry. This means that any work done by a seqlock reader running concurrently with a seqlock updater will be discarded and redone.

So seqlock readers can *run* concurrently with updaters, but they cannot actually get any work done in this case.

In contrast, RCU readers can perform useful work even in presence of concurrent RCU updaters.

Quick Quiz 2: What prevents the `list_for_each_entry_rcu()` from getting a segfault if it happens to execute at exactly the same time as the `list_add_rcu()`?

Answer: On all systems running Linux, loads from and stores to pointers are atomic, that is, if a store to a pointer occurs at the same time as a load from that same pointer, the load will return either the initial value or the value stored, never some bitwise mashup of the two. In addition, the `list_for_each_entry_rcu()` always proceeds forward through the list, never looking back. Therefore, the `list_for_each_entry_rcu()` will either see the element being

added by `list_add_rcu()`, or it will not, but either way, it will see a valid well-formed list.

Back to Quick Quiz 2.

Quick Quiz 3: Why do we need to pass two pointers into `hlist_for_each_entry_rcu()` when only one is needed for `list_for_each_entry_rcu()`?

Answer: Because in an hlist it is necessary to check for NULL rather than for encountering the head. (Try coding up a single-pointer `hlist_for_each_entry_rcu()`. If you come up with a nice solution, it would be a very good thing!)

Back to Quick Quiz 3.

Quick Quiz 4: How would you modify the deletion example to permit more than two versions of the list to be active?

Answer: One way of accomplishing this is as follows:

```
spin_lock(&mylock);
p = search(head, key);
if (p == NULL)
        spin_unlock(&mylock);
else {
        list_del_rcu(&p->list);
        spin_unlock(&mylock);
        synchronize_rcu();
        kfree(p);
}
```

Note that this means that multiple concurrent deletions might be waiting in `synchronize_rcu()`.

Back to Quick Quiz 4.

Quick Quiz 5: How many RCU versions of a given list can be active at any given time?

Answer: That depends on the synchronization design. If a semaphore protecting the update is held across the grace period, then there can be at most two versions, the old and the new.

However, if only the search, the update, and the `list_replace_rcu()` were protected by a lock, then there could

be an arbitrary number of versions active, limited only by memory and by how many updates could be completed within a grace period. But please note that data structures that are updated so frequently probably are not good candidates for RCU. That said, RCU can handle high update rates when necessary.

Back to Quick Quiz 5.

Quick Quiz 6: How can RCU updaters possibly delay RCU readers, given that the `rcu_read_lock()` and `rcu_read_unlock()` primitives neither spin nor block?

Answer: The modifications undertaken by a given RCU updater will cause the corresponding CPU to invalidate cache lines containing the data, forcing the CPUs running concurrent RCU readers to incur expensive cache misses. (Can you design an algorithm that changes a data structure *without* inflicting

expensive cache misses on concurrent readers? On subsequent readers?)

Back to Quick Quiz 6.

---

example code nitpicks

Posted Dec 20, 2007 21:15 UTC (Thu) by **ntl** (subscriber, #40518)

[Link]

Shouldn't the list_head and hlist_node structs be embedded in struct foo, instead of pointers? That is,

```
struct foo {
-   struct list_head *list;
+   struct list_head list;
    ...
}
```

Also, no need to cast the return value of kmalloc :)

example code nitpicks

Posted Dec 21, 2007 1:03 UTC (Fri)

by **PaulMcKenney** (subscriber, #9624) [Link]

Good catch in both cases!

example code nitpicks

Posted Dec 21, 2007 17:08 UTC (Fri)

by **PaulMcKenney** (subscriber, #9624) [Link]

And many thanks to Jon Corbet for applying the fixes for these problems!

Problem with ex 2 ?

Posted Dec 23, 2007 23:23 UTC (Sun) by **xav** (subscriber, #18536) [Link]

It looks to me that example 2 is wrong: access to p is unlocked, so it can changed under its feet if preempted: *q = *p can access freed memory.

Problem with ex 2 ?

Posted Dec 27, 2007 18:57 UTC (Thu)

by **PaulMcKenney** (subscriber, #9624) [Link]

Indeed! As with the preceding example, there must be some sort of mutual exclusion in play, and as in the preceding example, this mutual exclusion is not shown explicitly.

One approach, as you say, would be to add locking, perhaps similar to that described in the

answer to Quick Quiz 4 (but for the deletion example). Another approach would be to hold a mutex (in the old style, "semaphore") across the entire code segment. Yet a third approach would be to permit only a single designated task to do updates (in which case the code would remain as is). There are other approaches as well.

In any case, I am glad to see that people are sensitized to the need for mutual exclusion in parallel code!

What is RCU, Fundamentally?

Posted Dec 26, 2007 12:54 UTC (Wed) by **union** (guest, #36393)

[Link]

Since nobody else said it.

Thanks for a great article.

I liked the articles about memory and this looks like another great miniseries. While I spend most of my days programming python and Java,

I believe that understanding such lower level concepts makes me better programmer.

I hope that there will be more such background or fundamentals articles in the future.

Luka

What is RCU, Fundamentally?

Posted Dec 27, 2007 19:04 UTC (Thu)

by **PaulMcKenney** (subscriber, #9624) [Link]

Glad you liked it!!! ;-)

Garbage-collected languages such as Java implement RCU's "wait for pre-existing RCU readers to complete" implicitly via the garbage collector. However, in Java, you must make careful use of atomic variables in order to correctly implement the publish-subscribe mechanism. Last I knew, Java would emit memory barriers for the subscribe operation, even when unnecessary, but perhaps that has changed by now. However, in many cases, the memory-barrier overhead might well be acceptable (e.g., when avoiding contention).

So you might well be able to use RCU techniques in Java! (For whatever it is worth, Kung and Lehman described the gist of using garbage collectors in this fashion in their paper entitled "Concurrent Maintenance of Binary Search Trees" in "ACM Transactions on Database Systems" back in September 1980.)

What is RCU, Fundamentally?

Posted Dec 27, 2007 23:47 UTC (Thu) by **scottt** (subscriber, #5028) [Link]

A link to the paper.

With people doing all these advanced concurrent algorithms in the eighties I wonder why we're only just now getting a formal memory model for the C/C++ programming languages.

What is RCU, Fundamentally?

Posted Dec 28, 2007 15:22 UTC (Fri)

by **PaulMcKenney** (subscriber, #9624) [Link]

Thank you for providing the link -- much better than my old hard copy! It is very good indeed to see some of these older papers becoming available on the web.

There was indeed some memory-consistency-model research done some decades ago. Although I cannot claim comprehensive knowledge of memory-model research, as near as I can tell, almost all of this older research was swept aside by the notion of sequential consistency in 1979. The lion's share of later research assumed sequential consistency, which rendered this research less than helpful on weakly-ordered machines, where "weakly ordered" includes x86. Algorithms that fail to work on x86 cannot be said to have much practical value, in my opinion.

There were nevertheless some fundamental papers published in the 90s (e.g., Sarita Adve and Kourosh Gharachorloo, among others), but many of the researchers focused on "how to emulate sequential consistency on weak-memory machines" as opposed to "how best to express memory-ordering constraints while allowing efficient code to be generated for systems with a wide variety of memory consistency models". It is this latter statement that the C/C++ standards committee must address.

Backlinks

Posted Dec 28, 2007 12:37 UTC (Fri) by **mmutz** (guest, #5642)

[Link]

I'm wondering whether the omission of the backlinks in the examples is a good thing. The omission makes the technique trivial, since publishing only involves one replacing one pointer.

What about the second, back, one? Without support for atomic two-pointer updates, how can both the p->prev->next = q and p->next->prev = q updates be performed without risking clients to see an inconsistent view of the doubly linked list? Or is that not a problem in practice?

Thanks for the article, though. Looking forward to the next installment!

Backlinks

Posted Dec 28, 2007 15:35 UTC (Fri)

by **PaulMcKenney** (subscriber, #9624) [Link]

Glad you liked the article, and thank you for the excellent question! I could give any number of answers, including:

1. In production systems, trivial techniques are a very good thing.
2. Show me an example where it is useful to traverse the ->prev pointers under RCU protection. Given several such examples, we could work out how best to support this.
3. Consistency is grossly overrated. (Not everyone agrees with me on this, though!)
4. Even with atomic two-pointer updates, consider the following sequence of events: (1) task 1 does p=p->next (2) task 2 inserts a new element between the two that

task 1 just dealt with (3) task 1 does p=p->prev and fails to end up where it started! Even double-pointer atomic update fails to banish inconsistency! ;-)

5. If you need consistency, use locks.

Given the example above, we could support a level of consistency equivalent to the double-pointer atomic update simply by assigning the pointers in sequence -- just remove the prev-pointer poisoning from list_del_rcu(), for example. But doing this would sacrifice the ability to catch those bugs that pointer-poisoning currently catches.

So, there might well come a time when the Linux kernel permits RCU-protected traversal of linked lists in both directions, but we need to see a compelling need for this before implementing it.

Forcing the compiler and CPU to execute assignment statements in order ?

Posted Dec 30, 2007 16:51 UTC (Sun) by **Brenner** (subscriber, #28232) [Link]

Thanks for the article;

In the 'Publish-Subscribe Mechanism', the article states : "Unfortunately, there is nothing forcing the compiler and CPU to execute the last four assignment statements in order."

This breaks my mind. I understand concurrency problems with multiple tasks, but here only one task is considered (or did I misunderstand something ?). Why would the CPU not execute the last four assignment statements in the order given by the compiler, and why would the compiler not keep the order given by the programmer ???

Even with multiple tasks, I thought that the order was guaranteed (I agree that many things can happen between two code lines of one given task if other tasks are running though).

Can anyone enlighten me ?

Forcing the compiler and CPU to execute assignment statements in order ?

Posted Jan 1, 2008 23:10 UTC (Tue)

by **PaulMcKenney** (subscriber, #9624) [Link]

You are welcome!

Your question about ordering is a good one, and code reordering by both CPU and compiler can be grossly counter-intuitive at times. So an explanation is indeed in order. Let's start with the compiler. The code was as follows:

```
11 p->a = 1;
12 p->b = 2;
13 p->c = 3;
14 gp = p;
```

It is possible that the compiler holds the value of `gp` in a register, but that it will need to spill that value in order to generate the code for lines 11–14. What to do? Well, as long as the compiler can prove that `p` and `gp` do not point to overlapping regions of memory, the compiler is within its rights to generate the code for line 14 before generating the code for the other lines. In this case, rearranging the code in this manner reduces code size, probably increases performance, and hurts no one. That is, it hurts no one *in the absence of concurrency*. However, please keep in mind that the C standard currently does not allow

concurrency, strange though that may seem to those of us who have been writing concurrent C programs for decades.

So special non-standard compiler directives (`barrier()` in the Linux kernel, or, when used properly, `volatile`) are required to force the compiler to maintain ordering. Note that such directives are included, either directly or indirectly, in primitives that require ordering, for example, the `smp_mb()` memory barrier in the Linux kernel.

On to the CPU. Suppose that the compiler generates the code in order, and that the CPU executes it in order. What could possibly go wrong?

The store buffer. The CPU will likely commit the new values of `p->a`, `p->b`, `p->c`, and `gp` to the store buffer. If the cache line referenced by `p` happens to be owned by some other CPU (for example, if the memory returned by the preceding `kmalloc()` had

been `kfree()`ed by some other CPU) and if the cache line containing `gp` is owned by the current CPU, the first three assignments will be flushed from the store buffer (and thus visible to other CPUs) long after the last assignment will be.

In addition, superscalar CPUs routinely execute code out of order. Such beasts might become less common as power–consumption concerns rise to the fore, but there are still quite a few such CPUs out there, dating from the mid–1990s for commodity microprocessors and to the mid–*1960s* for supercomputers. For example, Tomasulo's Algorithm, dating from the mid–1960s, is specifically designed to allow CPUs to execute instructions out of order. And there were super–scalar supercomputers pre–dating Tomasulo's Algorithm.

In short, if ordering is important to you, use primitives to enforce ordering. Such primitives include locking primitives (e.g., `spin_lock()` and `spin_unlock()` in the Linux kernel), the RCU

publish–subscribe primitives called out in this article, and of course explicit memory barriers. (I would recommend avoiding explicit memory barriers where feasible -- they are difficult to get right.)

Hey, you asked!!! And Happy New Year!!!

Forcing the compiler and CPU to execute assignment statements in order ?

Posted Jan 2, 2008 0:09 UTC (Wed) by **Brenner** (subscriber, #28232) [Link]

Thanks a lot for your very informative answer. And Happy New Year!!!

Userland

Posted Jan 4, 2008 4:06 UTC (Fri) by **eduardo.juan** (guest, #47737) [Link]

Thanks for this excellent article!

I have a fundamentally question! :D

Is any way to use RCU on userland programs? I mean, any lib or implementation of this

constraints in userland?

Thanks and regards!

Using RCU in userland

Posted Jan 4, 2008 18:13 UTC (Fri)

by **PaulMcKenney** (subscriber, #9624) [Link]

RCU has been used experimentally in user-mode code, and one benchmarking framework may be found at U. of Toronto.

In addition, I vaguely recall at least one user-level RCU implementation being posted on LKML as a programming/debugging aid. There are some others that I am unfortunately unable to release at this time.

As noted in an earlier comment, garbage-collected languages automatically provide much of the wait-for-reader functionality for free -- however, it is still necessary to correctly handle the publish-subscribe operation correctly. One way to do this in Java

is to use the recently added "volatile" field specifier (no relation to "volatile" in C/C++) for the pointer that is being published. In other words, instead of using the Linux-kernel rcu_assign_pointer() and rcu_dereference() to publish and subscribe, you instead mark the pointer itself using Java's "volatile" keyword.

Using RCU in userland

Posted Jan 4, 2008 20:08 UTC (Fri) by **eduardo.juan** (guest, #47737) [Link]

Thanks Paul for answering! I'll be trying it!

Regards

Using RCU in userland

Posted Jan 5, 2008 16:26 UTC (Sat)

by **PaulMcKenney** (subscriber, #9624) [Link]

Very cool! Please let me know how it goes!

Some usages of RCU in the kernel code

Posted Jan 6, 2008 10:42 UTC (Sun) by **fbh** (subscriber, #49754)

[Link]

Hi,

I'm probably missing something but I looked at users of RCU in the kernel and found that kernel/kprobes.c doesn't call rcu_read_lock() function before entering in a critical section. Does it have any good reasons to do so ?

Another point in include/linux/list.h: sometimes it seems that RCU API is not used for no good reasons. For example __list_add_rcu() does not use rcu_dereference(). However by using it, the code could have clearly showed which pointer is RCU protected...

The Alpha memory ordering and value-speculation compiler optimizations done in this architecture sounds incredibely weird to me. Any avalaible pointers on this subject ?

Anyways, thanks for this article.

Some usages of RCU in the kernel code

Posted Jan 6, 2008 19:04 UTC (Sun)

by **PaulMcKenney** (subscriber, #9624) [Link]

The reason that kernel/kprobes.c does not use `synchronize_rcu()` is that it instead uses `synchronize_sched()`. The read-side primitives corresponding to `synchronize_sched()` include `preempt_disable()/preempt_enable()`, `loc`

`al_irq_save()/local_irq_restore()` -- in short, any primitive that disables and re-enables preemption, including entry to hardware irq/exception handlers. The third article in this series will cover these and other nuances of the RCU API.

The reason that `__list_add_rcu()` does not use `rcu_dereference()` is that `__list_add_rcu()` is an update-side primitive, and therefore must be protected by appropriate locking. This means that the list cannot change while the lock is held, and this in turn means that the memory barriers implied by lock acquisition suffice. That said, it is permissible (but again, not necessary) to use `rcu_dereference()` in update-side code -- in fact, in some situations, doing so promotes code reuse and in some cases readability.

The discussion of Figure 2 in this article and its bibliography is a good place to start on Alpha's memory ordering. I am not all that

familiar with value–speculation compiler–optimization research,

but one place to start might be here.

Some usages of RCU in the kernel code

Posted Jan 7, 2008 10:14 UTC (Mon) by **fbh** (subscriber, #49754)

[Link]

Regarding the second point, I'm sorry, my fingers typed rcu_dereference() whereas my brain was thinking to rcu_assign_pointer(). rcu_dereference() could be used in update-side code, as you pointed out, but obviously not in __list_add_rcu().

Therefore __list_add_rcu() could be:

```
new->next = next;
new->prev = prev;
rcu_assign_pointer(prev->next, new);
next->prev = new;
```

The main advantage of this is readability IMHO.

You said that __list_add_rcu() must be protected by appropriate locking, and a memory barrier is implied by lock acquisition which should be enough. But __list_add_rcu() has a memory barrier in its implementation.

Thanks.

Some usages of RCU in the kernel code

Posted Jan 7, 2008 15:28 UTC (Mon)

by **PaulMcKenney** (subscriber, #9624) [Link]

Good point! Would you like to submit a patch?

Some usages of RCU in the kernel code

Posted Jan 7, 2008 16:03 UTC (Mon) by **fbh** (subscriber, #49754)

[Link]

Well, I actually raised 2 points and I'm not sure which one is the good one...

Could you please clarify ?

To answer your question, I don't have any problems for submitting a patch.

PS: This interface is pretty hard for discussing on an article. It's like bottom-posting

except we loose all its advantages... Just my 2 cents.

Some usages of RCU in the kernel code

Posted Jan 7, 2008 16:52 UTC (Mon)

by **PaulMcKenney** (subscriber, #9624) [Link]

I was inviting a patch for incorporating the smp_wmb() into the rcu_assign_pointer.

The lock acquisition makes rcu_dereference() unnecessary, but cannot enforce the ordering

provided by the smp_wmb()/rcu_assign_pointer().

Some usages of RCU in the kernel code

Posted Jan 8, 2008 11:02 UTC (Tue) by **jarkao2** (guest, #41960)

[Link]

Thanks for this (next) great article too! BTW, probably 'a' tiny fix needed:

"Maintain Multiple Versions of Recently Updated Objects

[...] Two examples are presented showing how a an element [...]"

Some usages of RCU in the kernel code

Posted Jan 8, 2008 14:13 UTC (Tue)

by **PaulMcKenney** (subscriber, #9624) [Link]

Good eyes!!!

What is RCU, Fundamentally?

Posted Aug 6, 2011 10:47 UTC (Sat) by **stock** (guest, #5849)

[Link]

"One key attribute of RCU is the ability to safely scan data, even though that data is being modified concurrently. To provide this ability for concurrent insertion, RCU uses what can be thought of as a publish–subscribe mechanism."

Does this not read like that once announced Microsoft Filesystem

called

WinFS ? From the WinFS wikipedia penal records :

http://en.wikipedia.org/wiki/WinFS

"WinFS (short for Windows Future Storage)[1] is the code name

for a

cancelled[2] data storage and management system project based

on

relational databases, developed by Microsoft and first

demonstrated

in 2003 as an advanced storage subsystem for the Microsoft

Windows

operating system, ...

[...]

WinFS includes a relational database for storage of information,

and allows any type of information to be stored in it, provided

there is a well defined schema for the type."

It's funny to see IBM, amongst others, explain the 'dirty' details

about 'RCU'

here on LWN.

Robert

--

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What is RCU, Fundamentally?

Posted Aug 6, 2011 13:51 UTC (Sat) by **nix** (subscriber, #2304)

[Link]

Does this not read like that once announced Microsoft Filesystem

called WinFS ?

No. WinFS was a 'store everything in a relational database' thing.

This is utterly different, nothing relational at all.

What is RCU, Fundamentally?

Posted May 24, 2015 12:50 UTC (Sun) by **firolwn** (guest, #96711)

[Link]

I really didn't understand Quick Quiz 5.

Why does semaphore affect the numbers of RCU version list?

What is RCU, Fundamentally?

Posted Jun 8, 2015 18:32 UTC (Mon)

by **PaulMcKenney** (subscriber, #9624) [Link]

In the following code, we have at most two versions:

```
mutex_lock(&my_mutex);
p = find_an_element(key);
list_del_rcu(&p->list);
synchronize_rcu();
kfree(p);
mutex_unlock(&my_mutex);
```

Only one task at a time may hold `my_mutex`, so there can be at most two versions of the list, the new one with the element

deleted, and for pre-existing readers, the old one with that element still in place. (When this article was written, the Linux kernel used semaphores for sleeplocks, but it now uses mutexes.)

In contrast, suppose that the mutex is held only across the deletion:

```
mutex_lock(&my_mutex);
p = find_an_element(key);
list_del_rcu(&p->list);
mutex_unlock(&my_mutex);
synchronize_rcu();
kfree(p);
```

In this case, many updaters could be waiting for grace periods in parallel, so there could be many concurrent versions of the list.