Extending RCU for Realtime and Embedded Workloads

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Overview

- Introduction to RCU
- Realtime response and Classic RCU
- Lower-overhead realtime read-side primitives
- More scalable grace-period detection
- Better balance of throughput and latency for RCU callback invocation
- Lower per-structure memory overhead
- Priority boosting of RCU read-side critical sections
- Sleepable RCU(?)
Introduction to RCU
Why Not Just Use Locks???
Or Atomic Instructions???

<table>
<thead>
<tr>
<th>CPUs</th>
<th>XServe</th>
<th>IBM POWER</th>
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- Atomic instructions and memory barriers are *expensive*...
- And are required for locks, which also impose deadlock, latency, ...
- RCU allows readers to avoid these expensive instructions.
- (Yes, one can just make all instructions expensive, but... Realtime???)
Introduction to RCU

- RCU is most often used as reader-writer lock
  - With **very** low-overhead (deterministic) readers
    - For non-CONFIG_PREEMPT:
      - #define rcu_read_lock()
      - #define rcu_read_unlock()
  - But readers run concurrently with writers
  - Writers must retain old versions: avoid trashing readers
Introduction to RCU

- RCU is an API, with multiple implementations
  - rcu_read_lock() and rcu_read_unlock()
  - synchronize_rcu() and call_rcu()
  - rcu_assign_pointer() and rcu_dereference()
  - (There are ~20 additional non-core members of the RCU API)
Introduction to RCU

- Multiple RCU implementations
  - “Classic RCU” leverages context switches
    - RCU read-side critical sections not permitted to block
    - Therefore, context switch means all RCU readers on that CPU done
    - Once all CPUs context-switch, *all* prior RCU readers are done
  - Realtime RCU implementations presented on later slides
**RCU and Reader-Writer Locking**

```c
int search(long key, int *result) {
    struct list_head *lp;
    struct el *p;

    read_lock();
    list_for_each_entry(p, head, lp) {
        if (p->key == key) {
            *result = p->data;
            read_unlock();
            return 1;
        }
    }
    read_unlock();
    return 0;
}
```

```c
int search(long key, int *result) {
    struct list_head *lp;
    struct el *p;

    rcu_read_lock();
    list_for_each_entry_rcu(p, head, lp) {
        if (p->key == key) {
            *result = p->data;
            rcu_read_unlock();
            return 1;
        }
    }
    rcu_read_unlock();
    return 0;
}
```
RCU and Reader-Writer Locking

```c
int delete(long key) {
    struct el *p;
    write_lock(&listmutex);
    list_for_each_entry(p, head, lp) {
        if (p->key == key) {
            list_del(&p->list);
            write_unlock(&listmutex);
            synchronize_rcu();
            kfree(p);
            return 1;
        }
    }
    write_unlock(&listmutex);
    return 0;
}
```

But note that RCU allows search and delete to run concurrently!
Not all algorithms permit this: in theory can transform, but hurts performance.
Other Uses for RCU

- Determine when all pre-existing SMIs/NMIs have completed
- Determine when all pre-existing irq handlers have completed
  - But -rt version of this needs work
  - Because -rt's irq handlers can be preempted
    - Thomas Gleixner has a fix for this
- Determine when all current readers have detected a change in mode
  - SRCU uses synchronize_sched() in this way
- Force each CPU to execute an smp_mb()
Realtime Response and RCU
Realtime Response and RCU

- What are realtime's requirements on RCU?
  - Reliable
  - Callable from IRQ
  - Preemptible read side
  - Small memory footprint
  - Synchronization-free read side
  - Independent of memory blocks
  - Freely nestable read side
  - Unconditional read-to-write upgrade
  - Compatible API
- *Italics* == trouble for Classic RCU
  - Because it suppresses preemption.
    - Which is really bad for realtime scheduling latency!!!
  - But otherwise you get limitless grace periods: OOM!!!
Realtime Response and RCU

Key:
- “n”: undesirable
- “N”: disqualifies from some situations
- “X”: immediate and total disqualification

<table>
<thead>
<tr>
<th>Feature</th>
<th>Reliable</th>
<th>Callable From IRQ</th>
<th>Preemptible Read Side</th>
<th>Small Memory Footprint</th>
<th>Sync-Free Reads</th>
<th>Indpt of Memory Blocks</th>
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<th>Uncond R-W Upgrade</th>
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Realtime Response and RCU

- The rest of this presentation looks at ways of improving 2.6.17-rt5 RCU
  - Reduce read-side overhead
  - Improve grace-period detection scalability
  - Improve callback throughput/latency
  - Lower per-structure memory overhead
  - Boost priority of RCU read-side critical sections
    - For example, when preempted or waiting on a lock
Realtime Read-Side Overhead
Realtime Read-Side Overhead

- **-rt**: atomic instructions and memory barriers
- **optatomic**: no atomics if no preemption
- **optmb**: no memory barriers if no preemption
- **nonatomic**: never atomic or memory barriers
  - Still working on stability and on performance
- For comparison: CONFIG_PREEMPT and non-CONFIG_PREEMPT
Realtime RCU Counters

<table>
<thead>
<tr>
<th>Previous Count</th>
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<tbody>
<tr>
<td>CPU 0</td>
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</tr>
<tr>
<td>CPU 1</td>
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</tr>
<tr>
<td>CPU 2</td>
<td>0</td>
</tr>
<tr>
<td>CPU 3</td>
<td>0</td>
</tr>
</tbody>
</table>

Each task references the counter that it incremented in `rcu_read_lock()`, allowing `rcu_read_unlock()` to decrement it (or them).

Each task keeps a counter of `rcu_read_lock()` nesting, so that only outermost `rcu_read_lock()` and `rcu_read_unlock()` access per-CPU counters
## Realtime RCU Animated

<table>
<thead>
<tr>
<th></th>
<th>Previous Count</th>
<th>Current Count</th>
</tr>
</thead>
<tbody>
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</tr>
<tr>
<td>CPU 1</td>
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</tr>
<tr>
<td>CPU 3</td>
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</tbody>
</table>

Initial state.
Realtime RCU Animated

<table>
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<tr>
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</tr>
</thead>
<tbody>
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<tr>
<td>CPU 3</td>
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<td>0</td>
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</tbody>
</table>

Task A `rcu_read_lock()`.
Realtime RCU Animated

<table>
<thead>
<tr>
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<tbody>
<tr>
<td>CPU 0</td>
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<tr>
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</table>

Task D rcu_read_lock().
### Realtime RCU Animated

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<td>CPU 2</td>
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<tr>
<td>CPU 3</td>
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</table>

Task C synchronize_rcu() entry: Counters “flip”, or reverse roles.
<table>
<thead>
<tr>
<th></th>
<th>Previous Count</th>
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<tbody>
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<td>CPU 2</td>
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<td>0</td>
</tr>
<tr>
<td>CPU 3</td>
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</table>

Task B `rcu_read_lock()`.
Task D \texttt{rcu\_read\_unlock}().
Task A `rcu_read_unlock()`, Task C `synchronize_rcu()` returns.
### Realtime RCU Animated

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<tr>
<td>CPU 3</td>
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</table>

Task B `rcu_read_unlock()`.

But what issues are we failing to consider?
Other Realtime RCU Issues

- Memory barriers!
- Concurrent `rcu_read_lock()` and `synchronize_rcu()`
  - What if counter-roles flip races with increment?
- Concurrent `rcu_read_lock()` and earlier `rcu_read_unlock()` that is now on other CPU?
- IRQ handler doing `rcu_read_lock()` after interrupting RCU read-side critical section?
- And so on...
2.6.17-rt5 rcu_read_lock()

```c
void rcu_read_lock(void)
{
    int flipctr;
    unsigned long oldirq;

    local_irq_save(oldirq);
    if (current->rcu_read_lock_nesting++ == 0) {
        flipctr = rcu_ctrlblk.completed & 0x1;
        smp_read_barrier_depends();
        current->rcu_flipctr1 = ((__get_cpu_var(rcu_flipctr)[flipctr]);
        atomic_inc(current->rcu_flipctr1);
        smp_mb__after_atomic_inc(); /* might optimize out... */
        if (unlikely(flipctr != (rcu_ctrlblk.completed & 0x1))) {
            current->rcu_flipctr2 =
                ((__get_cpu_var(rcu_flipctr)[!flipctr]);
            atomic_inc(current->rcu_flipctr2);
            smp_mb__after_atomic_inc(); /* might optimize out... */
        }
    }
    local_irq_restore(oldirq);
}
```
void rcu_read_unlock(void) {
    unsigned long oldirq;
    local_irq_save(oldirq);
    if (--current->rcu_read_lock_nesting == 0) {
        smp_mb__before_atomic_dec();
        atomic_dec(current->rcu_flipctr1);
        current->rcu_flipctr1 = NULL;
        if (unlikely(current->rcu_flipctr2 != NULL)) {
            atomic_dec(current->rcu_flipctr2);
            current->rcu_flipctr2 = NULL;
        }
    }
    local_irq_restore(oldirq);
}
2.6.17-rt5 RCU Read Side

- 172 ns on 700 MHz i386: could do better.
  - Atomic operations and memory barriers!!!
- But both rcu_read_lock() and rcu_read_unlock() disable preemption.
  - If rcu_read_lock() sees zero in its CPU's current counter, no one else can possibly change it.
  - If rcu_read_unlock() sees a value of one in a counter that it is to decrement, no one else can possibly change it.
- Optimization: Don't use atomic operations in this case.
```
void rcu_read_lock(void) {
    int flipctr;
    unsigned long oldirq;

    local_irq_save(oldirq);
    if (current->rcu_read_lock_nesting++ == 0) {
        flipctr = rcu_ctrlblk.completed & 0x1;
        smp_read_barrier_depends();
        current->rcu_flipctrl1 = &(__get_cpu_var(rcu_flipctrl)[flipctr]);
        current->rcu_read_lock_cpu = smp_processor_id();
        if (atomic_read(current->rcu_flipctrl1) == 0) {
            atomic_set(current->rcu_flipctrl1, atomic_read(current->rcu_flipctrl1) + 1);
            smp_mb();
        } else {
            atomic_inc(current->rcu_flipctrl1);
            smp_mb__after_atomic_inc(); /* will optimize out... */
        }
    }
    atomic_inc(current->rcu_flipctrl2 = &(__get_cpu_var(rcu_flipctrl)[!flipctr]);
    smp_mb__after_atomic_inc(); /* might optimize out... */
    local_irq_restore(oldirq);
}
```
void rcu_read_unlock(void) {
  unsigned long oldirq;

  local_irq_save(oldirq);
  if (--current->rcu_read_lock_nesting == 0) {
    if ((atomic_read(current->rcu_flipctr1) == 1) &&
        (current->rcu_read_lock_cpu == smp_processor_id())) {
      smp_mb();
      atomic_set(current->rcu_flipctr1, atomic_read(current->rcu_flipctr1) - 1);
    } else {
      smp_mb__before_atomic_dec();
      atomic_dec(current->rcu_flipctr1);
    }
    current->rcu_flipctr1 = NULL;
    if (unlikely(current->rcu_flipctr2 != NULL)) {
      atomic_dec(current->rcu_flipctr2);
      current->rcu_flipctr2 = NULL;
    }
  }
  local_irq_restore(oldirq);
}
• 232 ns on 700 MHz i386: got worse!!!
  – Because i386 memory barriers are atomics...
• Really need to get rid of the memory barriers
  – Because most are unneeded anyway!
  – Incorporate into grace-period processing...
“optatomic” Update Side

- Associate the required memory barriers with grace-period processing
  - Less common than read-side critical sections
  - Gross simplifications in diagram below
void rcu_read_lock(void)
{
    int flipctr;
    unsigned long oldirq;

    local_irq_save(oldirq);
    if (current->rcu_read_lock_nesting++ == 0) {
        flipctr = rcu_ctrlblk.completed & 0x1;
        smp_read_barrier_depends();
        current->rcu_flipctr1 = &(__get_cpu_var(rcu_flipctr)[flipctr]);
        current->rcu_read_lock_cpu = smp_processor_id();
        if (atomic_read(current->rcu_flipctr1) == 0) {
            atomic_set(current->rcu_flipctr1, atomic_read(current->rcu_flipctr1) + 1);
        } else {
            atomic_inc(current->rcu_flipctr1);
        }
    } else {
        atomic_inc(current->rcu_flipctr1);
    }
    if (unlikely(flipctr != (rcu_ctrlblk.completed & 0x1))) {
        current->rcu_flipctr2 = &(__get_cpu_var(rcu_flipctr)[!flipctr]);
        /* Can again optimize to non-atomic on fastpath. */
        atomic_inc(current->rcu_flipctr2);
    }
    local_irq_restore(oldirq);
}
void rcu_read_unlock(void)
{
  unsigned long oldirq;

  local_irq_save(oldirq);
  if (--current->rcu_read_lock_nesting == 0) {
    if ((atomic_read(current->rcu_flipctr1) == 1) &&
        (current->rcu_read_lock_cpu == smp_processor_id())) {
      atomic_set(current->rcu_flipctr1,
                 atomic_read(current->rcu_flipctr1) - 1);
    }
    else {
      atomic_dec(current->rcu_flipctr1);
    }
  }
  current->rcu_flipctr1 = NULL;
  if (unlikely(current->rcu_flipctr2 != NULL)) {
    atomic_dec(current->rcu_flipctr2);
    current->rcu_flipctr2 = NULL;
  }
  local_irq_restore(oldirq);
}
“optmb” Read Side

• 115 ns on 700 MHz i386: improvement!
• But code path is still long and slow
  – Want to get rid of all mb()s and atomics from read-side primitives
  – Use nested grace periods to simplify read-side!
    • After flipping the roles of the counters, wait until all CPUs acknowledge the flip: eliminate races
      – A nested grace period
    • Retain memory barriers in grace-period handling
      – But grace period now becomes “fuzzy”
      – Must wait for two grace periods rather than one
“nonatomic” rcu_read_lock()

```c
void rcu_read_lock(void)
{
  int idx;
  int nesting;
  unsigned long oldirq;

  local_irq_save(oldirq);
  nesting = current->rcu_read_lock_nesting;
  if (nesting != 0) {
    current->rcu_read_lock_nesting = nesting + 1;
  } else {
    idx = rcu_ctrlblk.completed & 0x1;
    smp_read_barrier_depends();
    barrier();
    __get_cpu_var(rcu_flipctr)[idx]++;
    barrier();
    current->rcu_read_lock_nesting = nesting + 1;
    barrier();
    current->rcu_flipctr_idx = idx;
  }
  local_irq_restore(oldirq);
}
```

Note: handles rcu_read_lock() from within NMI/SMI handlers
void rcu_read_unlock(void) {
    int idx;
    int nesting;
    unsigned long oldirq;

    local_irq_save(oldirq);
    nesting = current->rcu_read_lock_nesting;
    if (nesting > 1) {
        current->rcu_read_lock_nesting = nesting - 1;
    } else {
        idx = current->rcu_flipctr_idx;
        smp_read_barrier_depends();
        barrier();
        current->rcu_read_lock_nesting = nesting - 1;
        barrier();
        __get_cpu_var(rcu_flipctr)[idx]--;
    }
    local_irq_restore(oldirq);
}
“nonatomic” Read Side

- 94 ns on 700 MHz i386: much better!
  - But still a factor of nine slower than CONFIG_PREEMPT implementation of RCU...

- Next steps:
  - Integrate CPU hotplug, need that now...
  - Get rid of the interrupt disabling: major source of overhead at the moment
  - And maybe get rid of preemption disabling as well, though this might not be possible
    - Would like to dump the task-local increment, but it is needed in order to priority-boost RCU read-side tasks
    - Might be able to fold into priority disabling...
## Realtime Read-Side Overhead

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<tr>
<td>2.6.15 CONFIG_PREEMPT</td>
<td>393</td>
<td>10.87</td>
<td>0.06</td>
</tr>
<tr>
<td>2.6.15 non-CONFIG_PREEMPT</td>
<td>61</td>
<td>0.63</td>
<td>0.06</td>
</tr>
</tbody>
</table>

- Good news: well over halfway to CONFIG_PREEMPT.
- Bad news: almost an order of magnitude still to go.
- May be able to reduce further by removing local_irq_disable().
RCU Callback Throughput and Latency
RCU Callback Throughput and Latency

- Callback scheduling priority and batching
- SLAB_DESTROY_BY_RCU
  - Example: Christoph Lameter's struct-file patch
    - Greatly reduces the number of call_rcu() invocations
    - But requires read-side checks
- Self-limiting updates:
  - limiting number of call_rcu()s in flight
  - limiting update rate
  - update by trusted person
  - call_rcu_bh()
  - synchronize_rcu()
Per-Struct Callback Overhead
Some people want to use Linux 2.6 kernels on extremely small systems.

- 2 MB (yes, `megabytes`) of physical memory.
- The 8-byte overhead of struct `rcu_head` is a concern for these small systems.
- Can we make things better for Linux on tiny embedded systems?
Per-Struct Callback Overhead

- Possible approaches:
  1. Use synchronize_rcu() rather than call_rcu()
     - gives self-limiting property to updates
     - but can result in update bottleneck
  2. Use “union” to hide rcu_head overhead
     - must union with fields that are not used after removal
     - great when it works, but not always possible
  3. Shrink rcu_head structure by mapping functions
     - works on small machines (<16 MB RAM)
       - limits the number of RCU callback functions
       - only saves half of the rcu_head
       - requires a table to map function index to pointer (see next slide)
## Per-Struct Callback Overhead

### Diagram

- **Function Index**
- **Truncated “next” Pointer**
- **Offset**
- **Address**

### Table

<table>
<thead>
<tr>
<th>Function</th>
<th>Offset</th>
</tr>
</thead>
<tbody>
<tr>
<td>d_callback()</td>
<td>0</td>
</tr>
<tr>
<td>file_free_rcu()</td>
<td>1</td>
</tr>
<tr>
<td>rcu_torture_cb()</td>
<td>0</td>
</tr>
<tr>
<td>.</td>
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<td>.</td>
<td>.</td>
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<td>.</td>
<td>.</td>
</tr>
<tr>
<td><strong>Up to 1024 Entries</strong></td>
<td></td>
</tr>
</tbody>
</table>
• The first two seem preferable:
  – Use of synchronize_rcu() and the union save eight bytes rather than just four
  – They don't limit the addressing or the number of callback function
• But people interested in extremely small systems might wish to experiment with the squeezed-down struct rcu_head
RCU Read-Side Priority Boost
RCU Read-Side Priority Boost

- Problem: RCU read-side critical sections can be preempted by CPU-bound realtime tasks
  - Halts grace periods, results in OOM

```
rcu_read_lock()
Grace Period Never Ends...
rcu_read_unlock()
```

```
rcu_read_lock()  preemption...
```

```
CPU-bound realtime task...
```
“Correct” solution: Don't code realtime tasks to be CPU-bound
  - CPU-bound high-priority realtime tasks will prevent any lower-priority realtime tasks from meeting their deadlines
    • Possible exception: tight loop on one CPU, everything else on other CPUs
      • But -rt currently not structured to support this
        - But OOMing in response to a user-level bug is socially irresponsible: tough to debug

Real solution: allow RCU read-side critical sections to be priority boosted
  - When and how to boost priority?
When to Boost? How High?

- Nonsensical to boost in rcu_read_lock()
  - High overhead
  - Unnecessary in most cases: priority only matters when you are not running!
- Usually doesn't make sense to boost non-realtime tasks to realtime priorities
  - Unless low on memory: error condition
  - Could maintain a list of candidates for a second boost
- Challenge: race between boosting priority and rcu_read_unlock()
Sleepable RCU
Sleepable RCU

- Problem: RCU read-side sleep forbidden
  - Restricted exceptions in -rt
    - preemption and blocking for mutex, which can in principle be awakened via priority boosting
  - Reason: read-side sleeping can OOM
- Solution: per-subsystem grace periods
  - Each subsystem keeps a “struct srcu_struct”:
    - init_srcu_struct(&s), cleanup_srcu_struct(&s)
  - Read side must keep track of index:
    - idx = srcu_read_lock(&s); ... srcu_read_unlock(&s, idx);
  - Update side uses synchronize_srcu(&s)
  - No call_srcu() -- self-throttling update enforced
  - Sleeping read side holds up only its own updates
SRCU API

• void init_srcu_struct(struct srcu_struct *sp);
• void cleanup_srcu_struct(struct srcu_struct *sp);
• int srcu_read_lock(struct srcu_struct *sp);
• void srcu_read_unlock(struct srcu_struct *sp, int idx);
• void synchronize_srcu(struct srcu_struct *sp);
• long srcu_batches_completed(struct srcu_struct *sp);
SRCU Operation: Trick #1

- Variables “x” and “y” are initially both zero
- Task A:

```c
for (;;) {
    b = y; barrier(); a = x;
    BUG_ON(b == 0 || a == 1);
}
```

- Task B:

```c
x = 1;
synchronize_sched();
y = 1;
```

- Task A's assertion guaranteed *not* to fire
SRCU Operation: Trick #2

- Variables “x”, “y”, and “z” are initially both zero
- Task A:
  ```c
  for (;;) {
      c = z; barrier(); a = x;
      BUG_ON(c == 0 || a == 1);
  }
  ```
- Task B:
  ```c
  x = 1;
  synchronize_sched(); /* many smb_mb()s, etc. */
  y = 1;
  ```
- Task C:
  ```c
  for (;;) {
      if (y == 1) z == 1;
  }
  ```
- Task A's assertion guaranteed not to fire
srcu_read_lock()

```
1 int srcu_read_lock(struct srcu_struct *sp)
2 {
3   int idx;
4
5   preempt_disable();
6   idx = sp->completed & 0x1;
7   barrier();  /* ensure compiler looks -once- at sp->completed. */
8   per_cpu_ptr(sp->per_cpu_ref, smp_processor_id())->c[idx]++;
9   srcu_barrier();  /* ensure compiler won't misorder critical section. */
10  preempt_enable();
11  return idx;
12 }
```

```
1 #ifndef CONFIG_PREEMPT
2 #define srcu_barrier() barrier()
3 #else /* #ifndef CONFIG_PREEMPT */
4 #define srcu_barrier()
5 #endif /* #else #ifndef CONFIG_PREEMPT */
```
srcu_read_unlock()

```c
void srcu_read_unlock(struct srcu_struct *sp, int idx) {
    preempt_disable();
    srcu_barrier(); /* ensure compiler won't misorder critical section. */
    per_cpu_ptr(sp->per_cpu_ref, smp_processor_id())->c[idx]--;
    preempt_enable();
}
```
void synchronize_srcu(struct srcu_struct *sp) {
    int idx;

    idx = sp->completed;
    mutex_lock(&sp->mutex);

    if ((sp->completed - idx) >= 2) {
        mutex_unlock(&sp->mutex);
        return;
    }

    synchronize_sched();  /* Force memory barrier on all CPUs. */
    idx = sp->completed & 0x1;
    sp->completed++;
    synchronize_sched();  /* Force memory barrier on all CPUs. */
    while (srcu_readers_active_idx(sp, idx))
        schedule_timeout_interruptible(1);
    synchronize_sched();  /* Force memory barrier on all CPUs. */
    mutex_unlock(&sp->mutex);
}
Potential Uses of SRCU

- Notifier chains (see Alan Stern's patch)
- Possible latency fixes for reader-writer semaphores in -rt
- Possible way of waiting for preemptible irq handlers
  - However, there are other ways of fixing this
- But mostly just because people have been asking me for something like this for many more years than I care to admit to!!!
Conclusions

- Goal is to converge realtime RCU if at all possible (at least with CONFIG_PREEMPT)
  - Reduce testing/maintenance burden
- Significant progress possible on reducing struct rcu_head memory consumption
- SRCU available should there be latency issues with reader-writer semaphores
  - where readers **must** block
- Summary: RCU is still growing and evolving
  - More than a decade after Paul first thought it to be fully mature...
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