Deterministic Synchronization in Multicore Systems:
The Role of RCU

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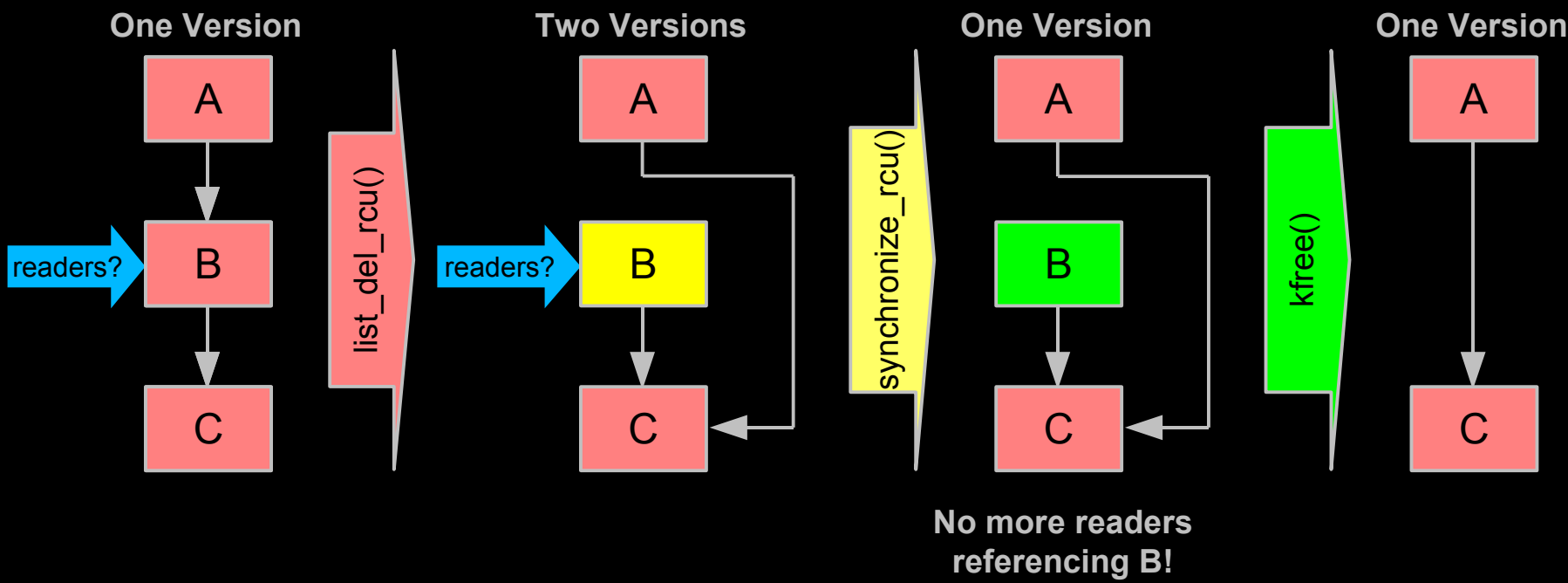
Overview

- A Brief Overview of RCU
- When to Use RCU (and not)
- Preemptible RCU: 2003, 2005, 2007, and 2009
- User-Level RCU

A Brief Overview of RCU

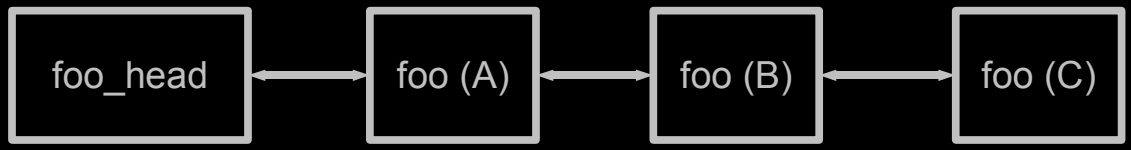
Brief Overview of RCU: Use Case

- Combines waiting for readers and multiple versions:
  - Writer removes element B from the list (list_del_rcu())
  - Writer waits for all readers to finish (synchronize_rcu())
  - Writer can then free B (kfree())
- Readers access the list with little or no synchronization



Brief Overview of RCU: Code for Use Case

```
struct foo_head {
   struct list_head list;
   spinlock_t mutex;
};

struct foo {
   struct list_head list;
   int key;
};
```

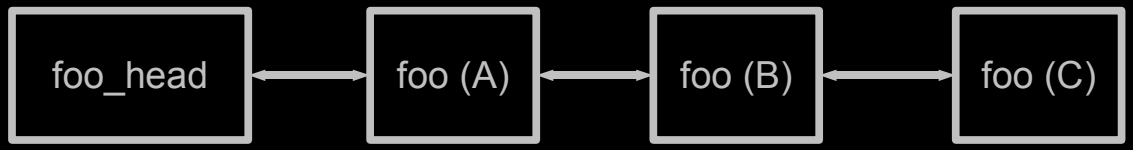



```
int search(struct foo_head *fhp, int k)
{
   struct foo *p;
   struct list_head *head = &fhp->list;

   rcu_read_lock();
   list_for_each_entry_rcu(p, head, list)
      if (p->key == k) {
         rcu_read_unlock();
         return 1;
      }
   }
   rcu_read_unlock();
   return 0;
}
```

```
int delete(struct foo_head *fhp, int k)
{
   struct foo *p;
   struct list_head *head = &fhp->list;

   spin_lock(&fhp->mutex);
   list_for_each_entry(p, head, list) {
      if (p->key == k) {
         list_del_rcu(p);
         spin_unlock(&fhp->mutex);
         synchronize_rcu();
         kfree(p);
         return 1;
      }
   }
   spin_unlock(&fhp->mutex);
   return 0;
}
```

Brief Overview of RCU: Code for rwlock

```
struct foo_head {
   struct list_head list;
   rwlock_t mutex;
};

struct foo {
   struct list_head list;
   int key;
};
```

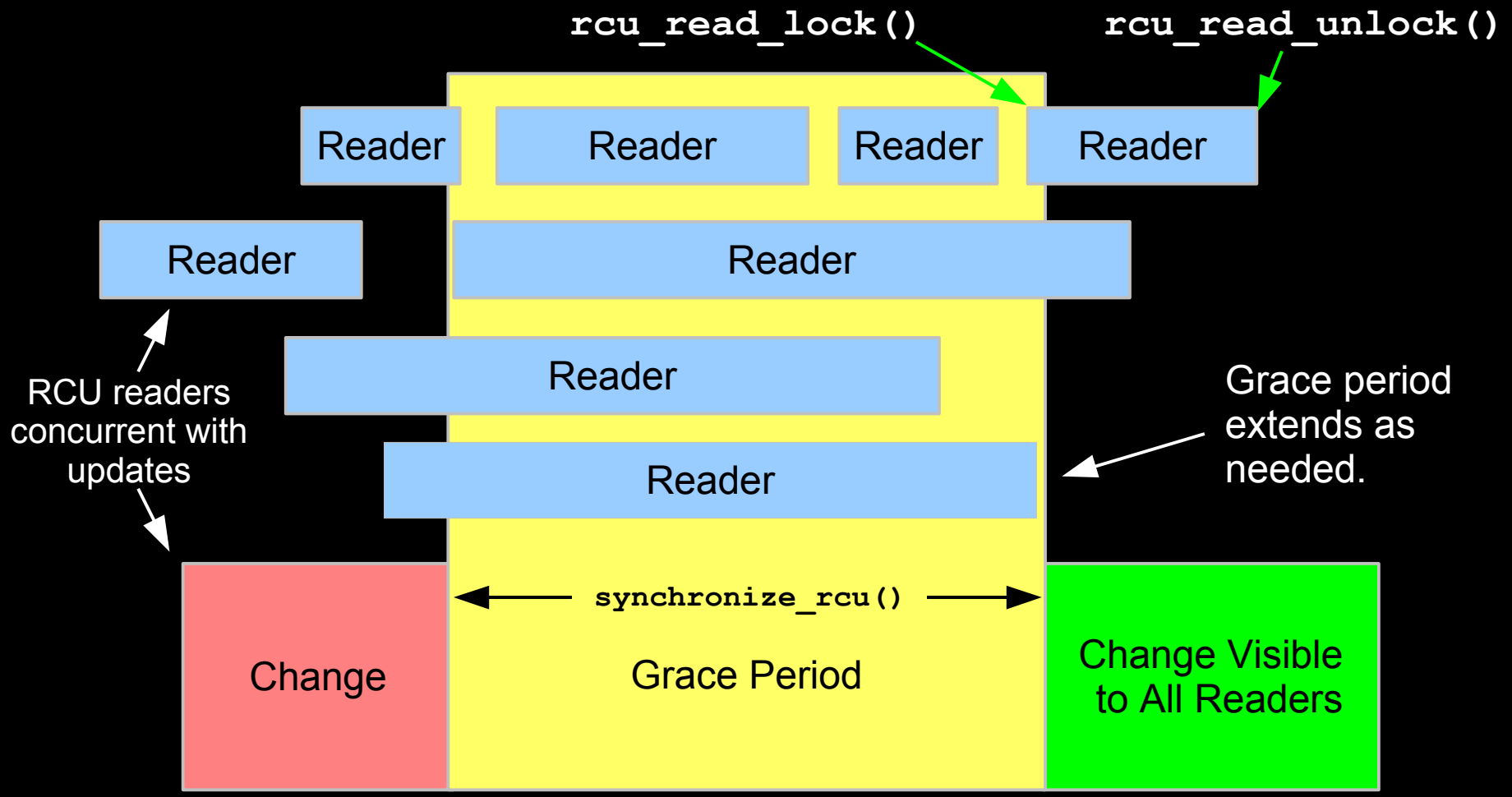



```
int search(struct foo_head *fhp, int k)
{
   struct foo *p;
   struct list_head *head = &fhp->list;

   read_lock(&fhp->mutex);
   list_for_each_entry(p, head, list) {
      if (p->key == k) {
         read_lock(&fhp->mutex);
         return 1;
      }
   }
   read_unlock(&fhp->mutex);
   return 0;
}
```

```
int delete(struct foo_head *fhp, int k)
{
   struct foo *p;
   struct list_head *head = &fhp->list;

   write_lock(&fhp->mutex);
   list_for_each_entry(p, head, list) {
      if (p->key == k) {
         list_del(p);
         write_unlock(&fhp->mutex);
         /* synchronize_rcu(); */
         kfree(p);
         return 1;
      }
   }
   write_unlock(&fhp->mutex);
   return 0;
}
```

What Does synchronize_rcu() Do???

Brief Overview of RCU: Waiting for Readers



A grace period is not permitted to end until all pre-existing readers have completed.

Brief Overview of RCU: Sort of Reference Count

```
struct foo *gp;
```

Publish

```
p = malloc(sizeof(p));
initialize(p);
rcu_assign_pointer(gp, p);
```

Publish

Retract

```
p = gp;
gp = NULL;
synchronize_rcu();
free(p);
```

Wait for pre-existing “references” to be released

Subscribe

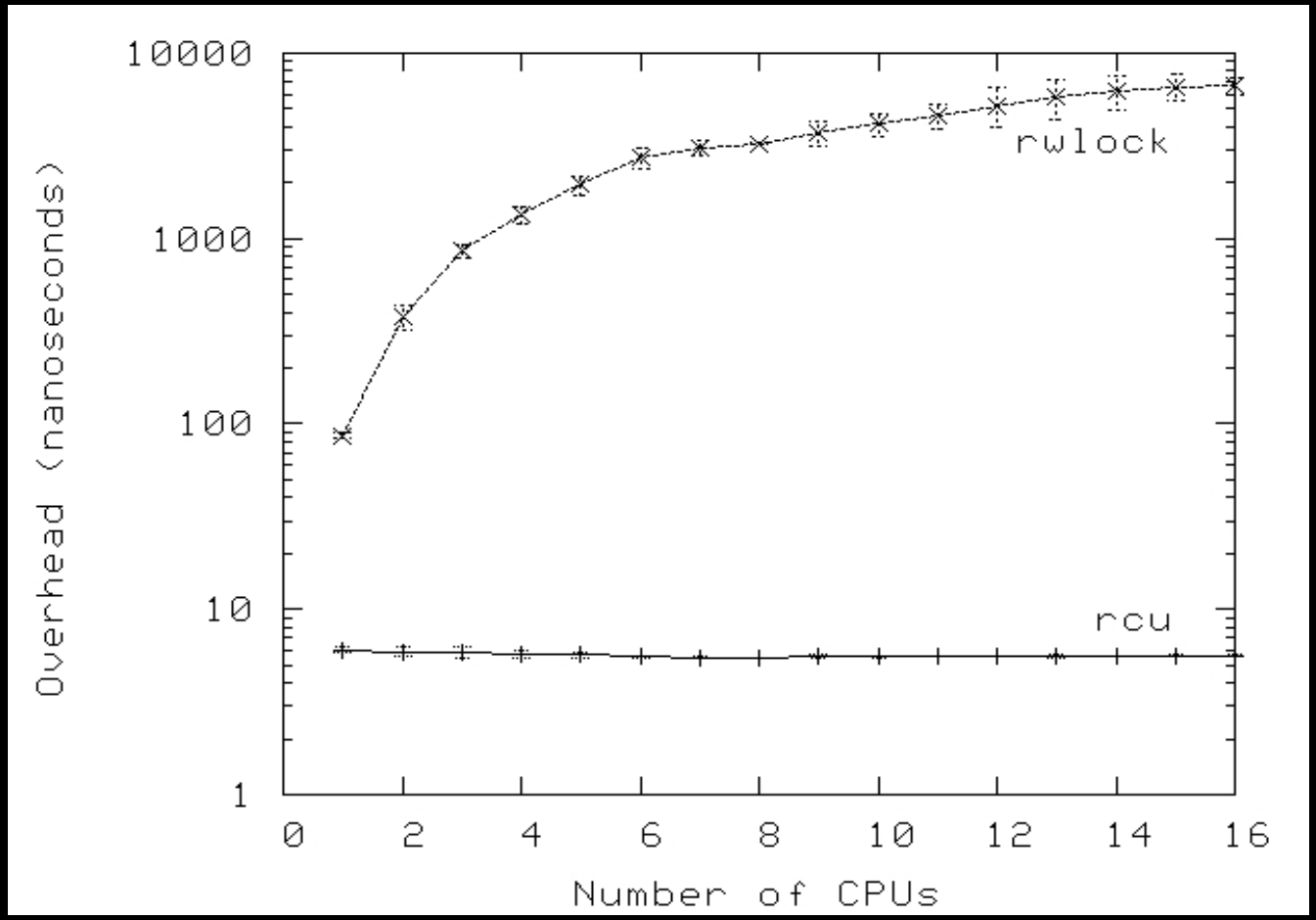
```
rcu_read_lock();
q = rcu_dereference(gp);
/* *q guaranteed to exist */
do_something_with(q);
rcu_read_unlock();
/* *q might be freed */
```

Acquire “reference”

Subscribe

Release “reference”

Brief Overview of RCU: Performance



CONFIG_PREEMPT kernel build

When to Use RCU (and not)

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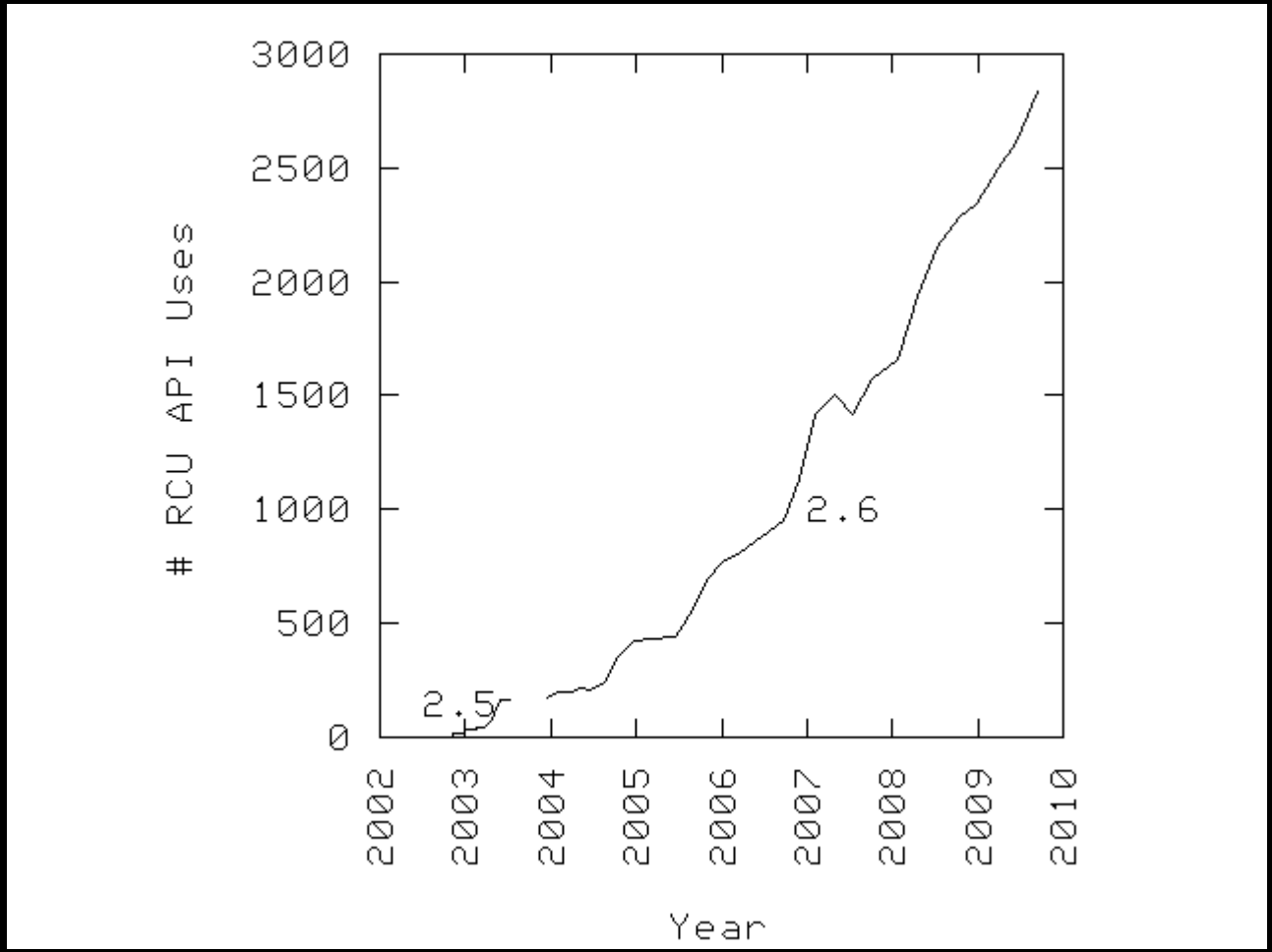
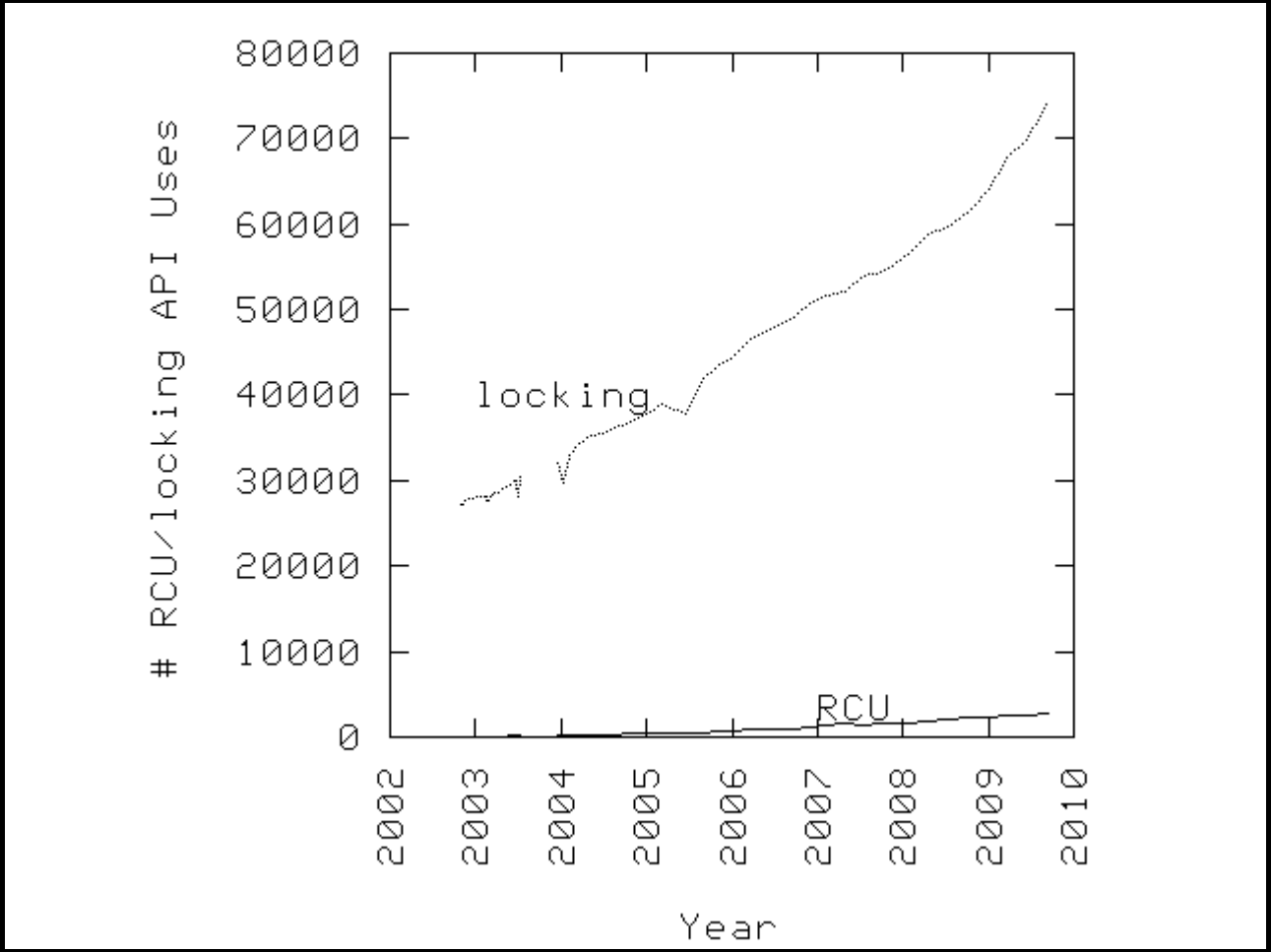
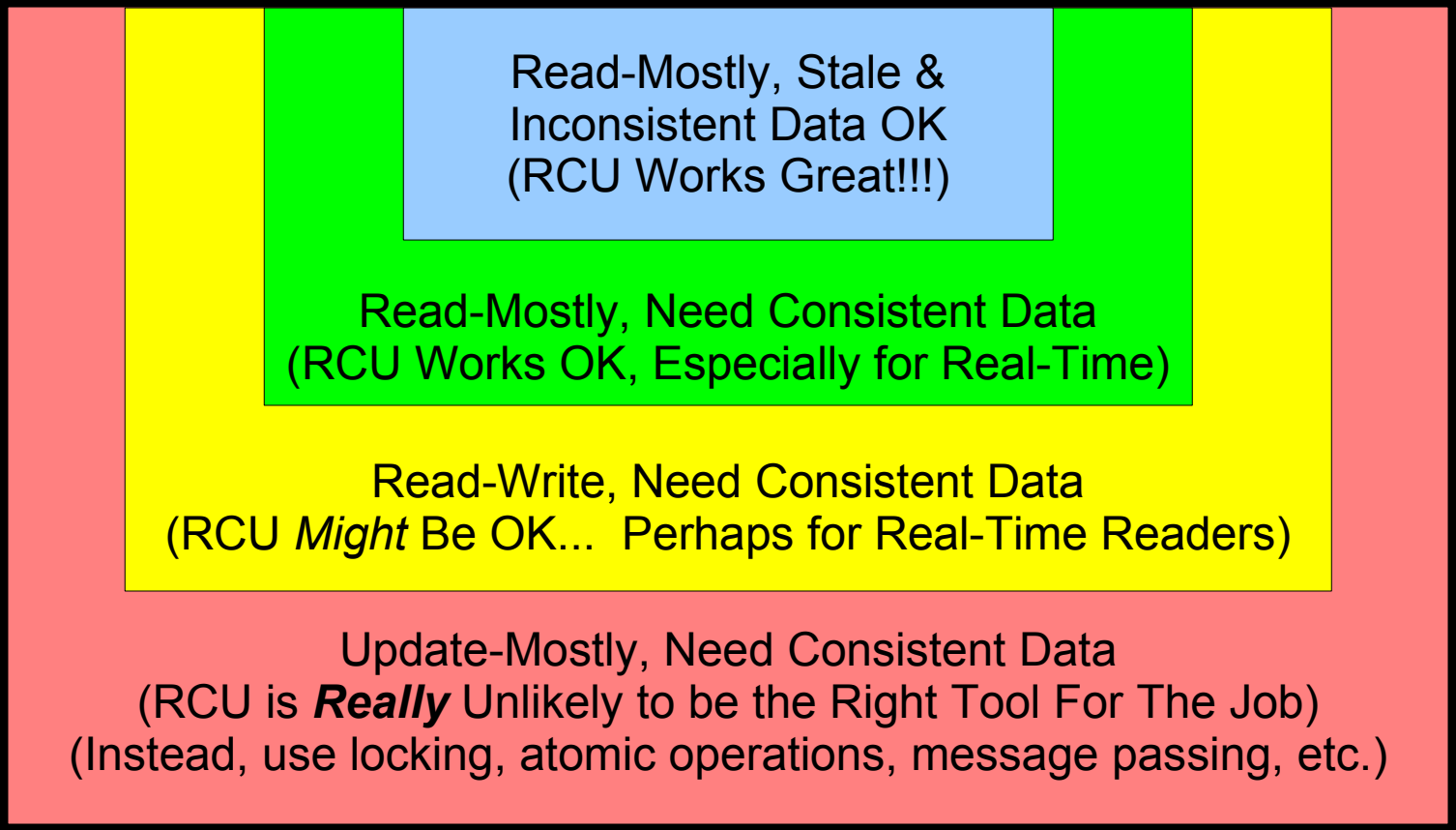


When to Use RCU (and not)



When to Use RCU (and not)



Preemptible RCU: 2003, 2005, 2007, and 2009

Non-Preemptible RCU: Classic RCU !PREEMPT

```
1 static inline void rcu_read_lock(void)
2 {
3 }
4
5 static inline void rcu_read_unlock(void)
6 {
7 }
```

Preemptible RCU: Classic RCU PREEMPT

```
1 static inline void rcu_read_lock(void)
2 {
3     preempt_disable();
4 }
5
6 static inline void rcu_read_unlock(void)
7 {
8     preempt_enable();
9 }
```

Preemptible RCU: 2005 Preemptible RCU

```
 1 void rcu_read_lock(void)
 2 {
 3   int f;
 4   unsigned long oldirq;
 5   struct task_struct *t = current;
 6
 7   raw_local_irq_save(oldirq);
 8   if (t->rcu_read_lock_nesting++ == 0) {
 9     f = rcu_ctrlblk.completed & 1;
10     smp_read_barrier_depends();
11     t->rcu_flipctr1 =
12       &(__get_cpu_var(rcu_flipctr)[f]);
13     atomic_inc(t->rcu_flipctr1);
14     smp_mb__after_atomic_inc();
15     if (f != (rcu_ctrlblk.completed & 1)) {
16       t->rcu_flipctr2 =
17         &(__get_cpu_var(rcu_flipctr)[!f]);
18       atomic_inc(t->rcu_flipctr2);
19       smp_mb__after_atomic_inc();
20     }
21   }
22   raw_local_irq_restore(oldirq);
23 }
```

```
 1 void rcu_read_unlock(void)
 2 {
 3   unsigned long oldirq;
 4   struct task_struct *t = current;
 5
 6   raw_local_irq_save(oldirq);
 7   if (--t->rcu_read_lock_nesting == 0) {
 8     smp_mb__before_atomic_dec();
 9     atomic_dec(t->rcu_flipctr1);
10     t->rcu_flipctr1 = NULL;
11     if (t->rcu_flipctr2 != NULL) {
12       atomic_dec(t->rcu_flipctr2);
13       t->rcu_flipctr2 = NULL;
14     }
15   }
16   raw_local_irq_restore(oldirq);
17 }
```

Preemptible RCU: 2007 Preemptible RCU

```
 1 void __rcu_read_lock(void)
 2 {
 3   int idx;
 4   struct task_struct *t = current;
 5   int nesting;
 6
 7   nesting = ACCESS_ONCE(t->rcu_read_lock_nesting);
 8   if (nesting != 0) {
 9     t->rcu_read_lock_nesting = nesting + 1;
10   } else {
11     unsigned long flags;
12
13     local_irq_save(flags);
14     idx = ACCESS_ONCE(rcu_ctrlblk.completed) & 0x1;
15     ACCESS_ONCE(RCU_DATA_ME()->rcu_flipctr[idx])++;
16     ACCESS_ONCE(t->rcu_read_lock_nesting) = nesting + 1;
17     ACCESS_ONCE(t->rcu_flipctr_idx) = idx;
18     local_irq_restore(flags);
19   }
20 }
```

```
 1 void __rcu_read_unlock(void)
 2 {
 3   int idx;
 4   struct task_struct *t = current;
 5   int nesting;
 6
 7   nesting = ACCESS_ONCE(t->rcu_read_lock_nesting);
 8   if (nesting > 1) {
 9     t->rcu_read_lock_nesting = nesting - 1;
10   } else {
11     unsigned long flags;
12
13     local_irq_save(flags);
14     idx = ACCESS_ONCE(t->rcu_flipctr_idx);
15     ACCESS_ONCE(t->rcu_read_lock_nesting) = nesting - 1;
16     ACCESS_ONCE(RCU_DATA_ME()->rcu_flipctr[idx])--;
17     local_irq_restore(flags);
18   }
19 }
```

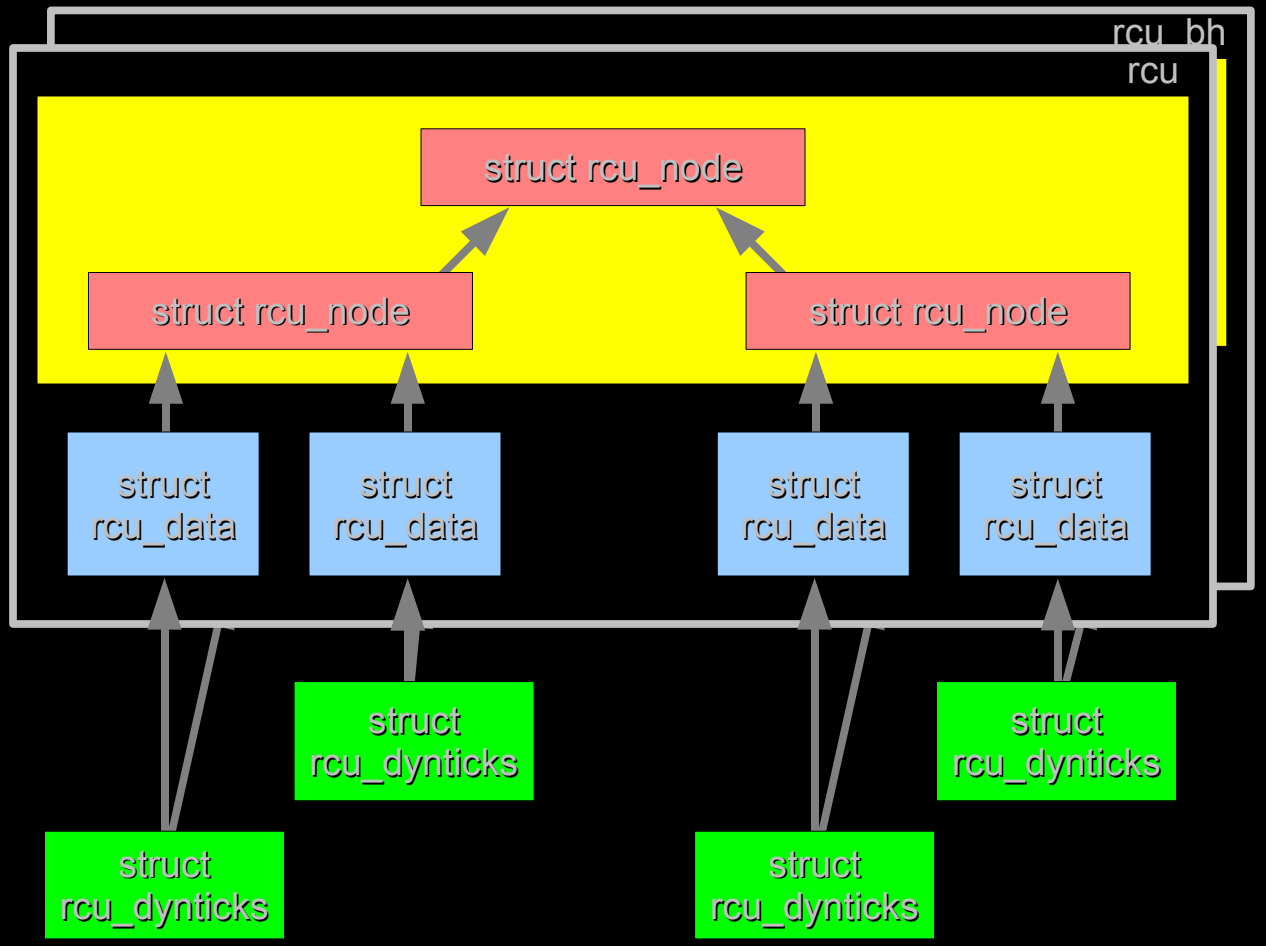
No longer the mainline preemptible RCU implementation

Preemptible RCU: 2009 Preemptible RCU

```
 1 void __rcu_read_lock(void)
 2 {
 3   ACCESS_ONCE(current->rcu_read_lock_nesting)++;
 4   barrier();
 5 }
 6
 7 void __rcu_read_unlock(void)
 8 {
 9   struct task_struct *t = current;
10
11   barrier();
12   if (--ACCESS_ONCE(t->rcu_read_lock_nesting) == 0 &&
13       unlikely(ACCESS_ONCE(t->rcu_read_unlock_special)))
14     rcu_read_unlock_special(t);
15 }
```

Accepted into mainline for 2.6.32 kernel

TREE_RCU Data Structures



TREE_RCU struct rcu_node

struct rcu_node

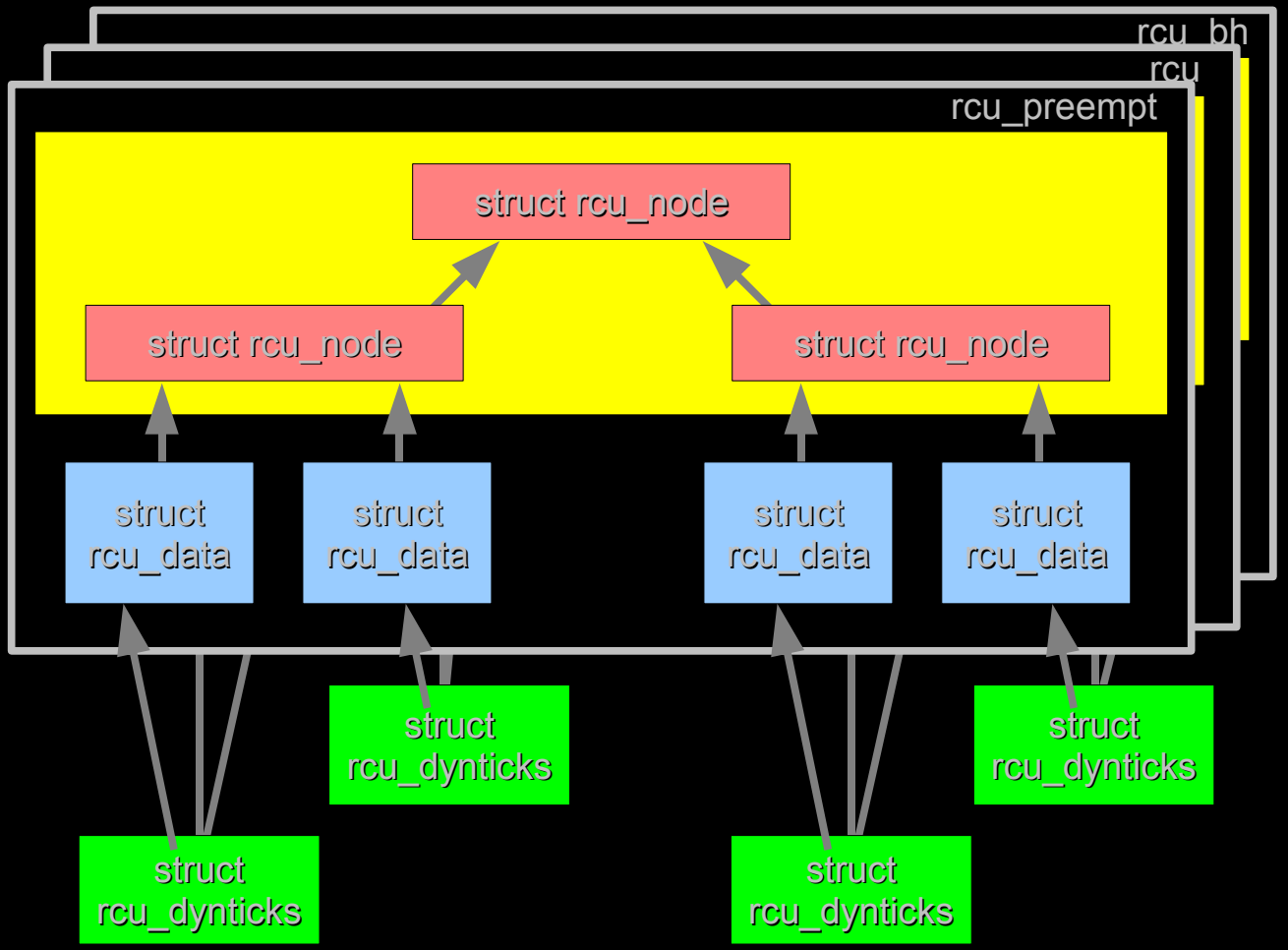
```
spinlock_t lock;
unsigned long qsmask;       /* CPUs waited for */
unsigned long qsmaskinit;   /* CPUs online */
unsigned long grpmask;      /* Bit in parent */
int grplo;                  /* First CPU/group # */
int grphi;                  /* Last CPU/group # */
u8 grpnum;                  /* Bit # in parent */
u8 level                    /* Root is level 0 */
struct rcu_node parent;     /* Pointer to parent */
```

TREE_PREEMPT_RCU struct rcu_node

struct rcu_node

```
spinlock_t lock;
long gpnum;                     /* Grace period # */
unsigned long qsmask;           /* CPUs waited for */
unsigned long qsmaskinit;       /* CPUs online */
unsigned long grpmask;          /* Bit in parent */
int grplo;                      /* First CPU/group # */
int grphi;                      /* Last CPU/group # */
u8 grpnum;                      /* Bit # in parent */
u8 level                        /* Root is level 0 */
struct rcu_node parent;         /* Pointer to parent */
struct list_head blocked_tasks[2];
                                /* In RCU R-S C-S */
```

TREE_PREEMPT_RCU Data Structures



Plug-In Architecture (kernel/rcutree_plugin.h)

```
static inline void rcu_bootup_announce(void);
long rcu_batches_completed(void);
static void rcu_preempt_note_context_switch(int cpu);
static int rcu_preempted_readers(struct rcu_node *rnp);
#ifdef CONFIG_RCU_CPU_STALL_DETECTOR
static void rcu_print_task_stall(struct rcu_node *rnp);
#endif /* #ifdef CONFIG_RCU_CPU_STALL_DETECTOR */
static void rcu_preempt_check_blocked_tasks(struct rcu_node *rnp);
#ifdef CONFIG_HOTPLUG_CPU
static void rcu_preempt_offline_tasks(struct rcu_state *rsp,
                                      struct rcu_node *rnp,
                                      struct rcu_data *rdp);
static void rcu_preempt_offline_cpu(int cpu);
#endif /* #ifdef CONFIG_HOTPLUG_CPU */
static void rcu_preempt_check_callbacks(int cpu);
static void rcu_preempt_process_callbacks(void);
void call_rcu(struct rcu_head *head, void (*func)(struct rcu_head
*rcu));
static int rcu_preempt_pending(int cpu);
static int rcu_preempt_needs_cpu(int cpu);
static void __cpuinit rcu_preempt_init_percpu_data(int cpu);
static void rcu_preempt_send_cbs_to_orphanage(void);
static void __init __rcu_init_preempt(void);
```

Planned Configuration Selection

	SMP	!SMP
PREEMPT	TREE_PREEMPT_RCU	TINY_PREEMPT_RCU (TBD)
!PREEMPT	TREE_RCU	TINY_RCU

User-Level RCU

User-Level RCU

- Multiple experimental implementations:
  - Hart et al. IPDPS'06
    http://www.rdrop.com/users/paulmck/RCU/hart_ipdps06.pdf
  - git://git.kernel.org/pub/scm/linux/kernel/git/paulmck/perfbook.git
- M. Desnoyers, 2009 Linux Plumbers Conference
  - Minimal read-side overhead
  - Library-ready implementation (read-side smp_mb())
  - Signal-based implementation
  - Likely to appear soon in a distro near you...
- Linux Audio project (P. Davis)
- And numerous others

Summary

- RCU is a specialized synchronization primitive that provides deterministic read-side overhead
- Kernel RCU implementation has grown increasingly simple and fast
  - "I would have provided a simpler implementation to start with, but I did not have time to do so."
- User-level RCU primitives used in production
  - A surprise to me...
  - And several production-quality implementations are under development
  - Likely to be useful in real-time applications

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- This material is based upon work supported by the National Science Foundation under Grant No. CNS-0719851.
  - Joint work with Manish Gupta, Maged Michael, Phil Howard, Joshua Triplett, Mathieu Desnoyers, and Jonathan Walpole

Questions?

- http://lwn.net/Articles/262464/ (What is RCU, Fundamentally?)
- http://lwn.net/Articles/263130/ (What is RCU's Usage?)
- http://lwn.net/Articles/264090/ (What is RCU's API?)
- http://www.rdrop.com/users/paulmck/RCU/lockperf.2004.01.17a.pdf
  - linux.conf.au paper comparing RCU vs. locking performance
- http://www.rdrop.com/users/paulmck/RCU/RCUdissertation.2004.07.14e1.pdf
  - RCU motivation, implementations, usage patterns, performance (micro+sys)
- http://www.livejournal.com/users/james_morris/2153.html
  - System-level performance for SELinux workload: >500x improvement
- http://www.rdrop.com/users/paulmck/RCU/hart_ipdps06.pdf
  - Comparison of RCU and NBS (later appeared in JPDC)
- http://doi.acm.org/10.1145/1400097.1400099
  - History of RCU in Linux (Linux changed RCU more than vice versa)
- git://lttng.org/userspace-rcu.git
  - Mathieu Desnoyers's user-space RCU git repository
- http://www.rdrop.com/users/paulmck/RCU/ (More RCU information)