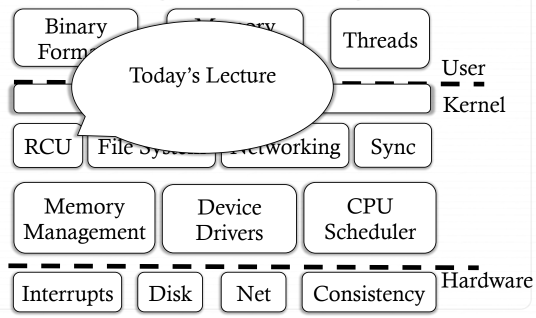
Read-Copy Update (RCU)

Don Porter
CSE 506

Logical Diagram

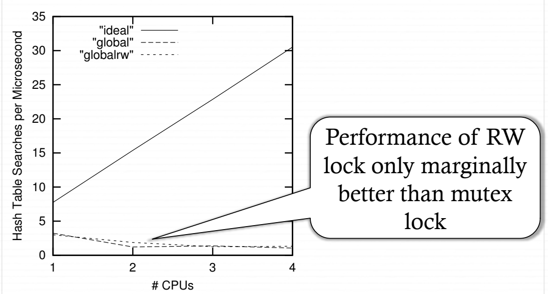


RCU in a nutshell

- Think about data structures that are mostly read, occasionally written
  - Like the Linux dcache
- RW locks allow concurrent reads
  - Still require an atomic decrement of a lock counter
  - Atomic ops are expensive
- Idea: Only require locks for writers; carefully update data structure so readers see consistent views of data

Motivation

(from Paul McKenney's Thesis)



Principle (1/2)

- Locks have an acquire and release cost
  - Substantial, since atomic ops are expensive
- For short critical regions, this cost dominates performance

Principle (2/2)

- Reader/writer locks may allow critical regions to execute in parallel
- But they still serialize the increment and decrement of the read count with atomic instructions
  - Atomic instructions performance decreases as more CPUs try to do them at the same time
- **The read lock itself becomes a scalability bottleneck, even if the data it protects is read 99% of the time**

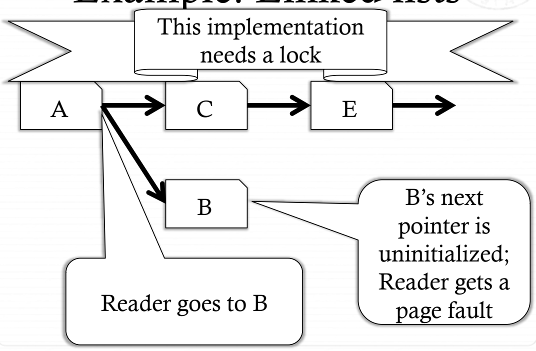
Lock-free data structures

- Some concurrent data structures have been proposed that don't require locks
- They are difficult to create if one doesn't already suit your needs; highly error prone
- Can eliminate these problems

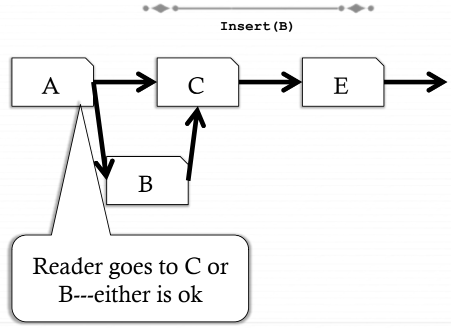
RCU: Split the difference

- One of the hardest parts of lock-free algorithms is concurrent changes to pointers
  - So just use locks and make writers go one-at-a-time
- But, make writers be a bit careful so readers see a consistent view of the data structures
- If 99% of accesses are readers, avoid performance-killing read lock in the common case

Example: Linked lists



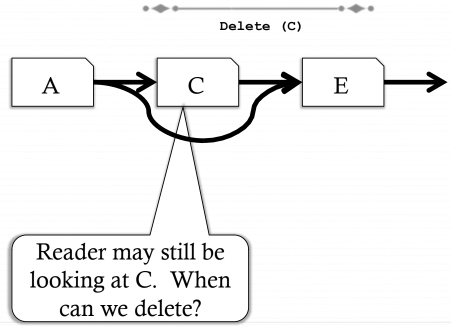
Example: Linked lists



Example recap

- Notice that we first created node B, and set up all outgoing pointers
- Then we overwrite the pointer from A
  - No atomic instruction or reader lock needed
  - Either traversal is safe
  - In some cases, we may need a memory barrier
- Key idea: Carefully update the data structure so that a reader can never follow a bad pointer
  - Writers still serialize using a lock

Example 2: Linked lists



Problem

- We logically remove a node by making it unreachable to future readers
  - No pointers to this node in the list
- We eventually need to free the node's memory
  - Leaks in a kernel are bad!
- When is this safe?
  - Note that we have to wait for readers to "move on" down the list

Worst-case scenario

- Reader follows pointer to node X (about to be freed)
- Another thread frees X
- X is reallocated and overwritten with other data
- Reader interprets bytes in X->next as pointer, segmentation fault

Quiescence

- Trick: Linux doesn't allow a process to sleep while traversing an RCU-protected data structure
  - Includes kernel preemption, I/O waiting, etc.
- Idea: If every CPU has called schedule() (quiesced), then it is safe to free the node
  - Each CPU counts the number of times it has called schedule()
  - Put a to-be-freed item on a list of pending frees
  - Record timestamp on each CPU
  - Once each CPU has called schedule, do the free

Quiescence, cont

- There are some optimizations that keep the per-CPU counter to just a bit
  - Intuition: All you really need to know is if each CPU has called schedule() once since this list became non-empty
  - Details left to the reader

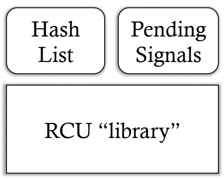
Limitations

- No doubly-linked lists
- Can't immediately reuse embedded list nodes
  - Must wait for quiescence first
  - So only useful for lists where an item's position doesn't change frequently
- Only a few RCU data structures in existence

Nonetheless

- Linked lists are the workhorse of the Linux kernel
- RCU lists are increasingly used where appropriate
- Improved performance!

Big Picture



- Carefully designed data structures
  - Readers always see consistent view
- Low-level "helper" functions encapsulate complex issues
  - Memory barriers
  - Quiescence

API

- Drop in replacement for read_lock:
  - rcu_read_lock()
- Wrappers such as rcu_assign_pointer() and rcu_dereference_pointer() include memory barriers
- Rather than immediately free an object, use call_rcu(object, delete_fn) to do a deferred deletion

Code Example

From fs/binfmt_elf.c

```
rcu_read_lock();

prstatus->pr_ppid =
     task_pid_vnr(rcu_dereference(p->real_parent));

rcu_read_unlock();
```

Simplified Code Example

From arch/x86/include/asm/rcupdate.h

```
#define rcu_dereference(p) ({                          \

 typeof(p) ______p1 = (*(volatile typeof(p)*) &p);\

 read_barrier_depends(); // defined by arch          \

 ______p1; // "returns" this value                   \

})
```

Code Example

From fs/dcache.c

```
static void d_free(struct dentry *dentry) {
      /* ... Ommitted code for simplicity */
      call_rcu(&dentry->d_rcu, d_callback);
}

// After quiescence, call_rcu functions are called

static void d_callback(struct rcu_head *rcu) {
      struct dentry *dentry =
         container_of(head, struct dentry, d_rcu);
      __d_free(dentry); // Real free
}
```

From McKenney and Walpole, Introducing Technology into the Linux Kernel: A Case Study

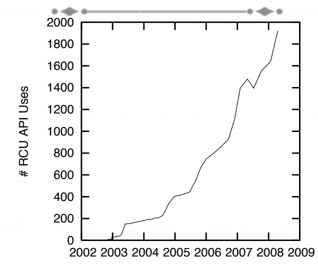


Figure 2: RCU API Usage in the Linux Kernel

Summary

- Understand intuition of RCU
- Understand how to add/delete a list node in RCU
- Pros/cons of RCU