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Advanced Operating Systems and Virtualization

[7] Concurrency in the Kernel

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2. **Synchronization**
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7.1

7. Concurrency in the Kernel

Introduction

Concurrency Properties

- **Safety**: nothing wrong happens, it is also called Correctness

  What does it mean for a program to be correct?

  Intuitively, if we rely on locks, changes happen in a non-interleaved fashion, resembling a sequential execution. We can say a parallel execution is correct **only because** we can associate it with a sequential one, which we know the functioning of

- **Liveness**: eventually something good happens, opposed to starvation and also called *Progress*

Correctness Conditions

The linearizability property tries to generalize the intuition of correctness. We call *history* a sequence of invocations and replies generated on an object by a set of threads.

A sequential history is a history where all the invocations have an immediate response.

A history is called **linearizable** if:

- invocations/responses can be reordered to create a sequential history
- the so-generated sequential history is correct according to the sequential definition of the object
- If a response precedes an invocation in the original history, then it must precede it in the sequential one as well

An object is linearizable if every valid history associated with its usage can be linearized.

Progress Conditions

- **Deadlock-free**: some thread acquires a lock eventually
- **Starvation-free**: every thread acquires a lock eventually
- **Lock-free**: some method call completes
- **Wait-free**: every method call completes
- **Obstruction-free**: every method call completes, if they execute in isolation

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7. Concurrency in the Kernel

Synchronization

Servicing requests

You can think about the kernel as a waiter that needs to serve requests from two kinds of customers: normal customers and bosses. The policy adopted is the following:

1. if a boss calls when the waiter is idle, the waiter serves the boss
2. if a boss calls when the waiter is serving a normal customer the waiter stops and serves the boss
3. if a boss calls when the waiter is servicing another boss it stops and start servicing the second, when done it continues to serve the first
4. when a boss induces the waiter to leave the current normal customer, the waiter after the last request from the bosses may decide to temporarily drop the old customer to pick a new one

Obviously a normal customer is a system call from a user space process and a boss is an interrupt.

Kernel Preemption

The last waiter's rule corresponds to the so-called kernel preemption (included from kernel 2.6). In general a kernel is preemptive *if **a process switch may occur while the replaced process is executing a kernel function**, that is when it runs in kernel mode*.

In the linux kernel:

- a process in kernel mode may relinquish voluntarily the CPU (e.g. for sleeping), we call this a **planned process switch**, however in preemptive kernels even if a process is in kernel mode reacts to asynchronous events that may lead to a process switch, we call this a **forced process switch**;
- all processes are switched with the `switch_to()` macro, both in preemptive and non-preemptive kernels a process switch occurs when a <u>process has finished</u> some thread of kernel <u>activity</u> and the scheduler is invoked, however in non-preemptive kernels a process cannot be replaced unless it is about to switch to User Mode.

Kernel Preemption

Preemption is managed with three counters, if the sum is greater than zero the preemption is disabled:

- the kernel is executing an Interrupt Service Routine
- deferrable functions are disabled
- preemption has been explicitly disabled (`preempt_disable()`)

Table 5-1. Macros dealing with the preemption counter subfield

Macro	Description
`preempt_count()`	Selects the `preempt_count` field in the `thread_info` descriptor
`preempt_disable()`	Increases by one the value of the preemption counter
`preempt_enable_no_resched()`	Decreases by one the value of the preemption counter
`preempt_enable()`	Decreases by one the value of the preemption counter, and invokes `preempt_schedule()` if the `TIF_NEED_RESCHED` flag in the `thread_info` descriptor is set
`get_cpu()`	Similar to `preempt_disable()`, but also returns the number of the local CPU
`put_cpu()`	Same as `preempt_enable()`
`put_cpu_no_resched()`	Same as `preempt_enable_no_resched()`

Bovet, Daniel P., and Marco Cesati. *Understanding the Linux Kernel: from I/O ports to process management*. " O'Reilly Media, Inc.", 2005.

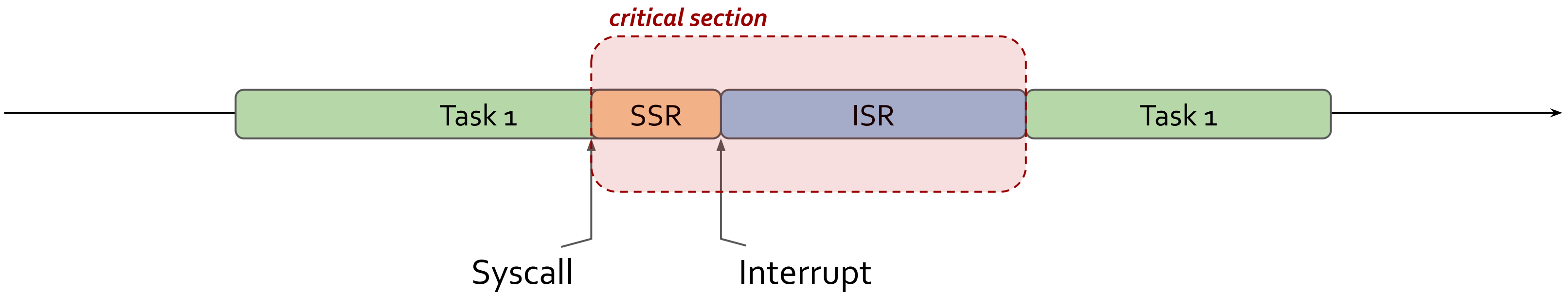
When Synchronization is Necessary

A race condition can occur when the outcome of the computation depends on how two or more interleaved kernel control path are nested. A critical region is a section of the code that must be completely executed by the kernel control path that enters it before another kernel control path can execute it.

Suppose that two different interrupt handlers need to access the same data structure, all statements that access the data structure must be put in a critical region. On a single CPU you can disable the interrupts and the preemption, but this **is not enough** in a multi-processor system.

When Synchronization is Necessary

System Calls and Interrupts



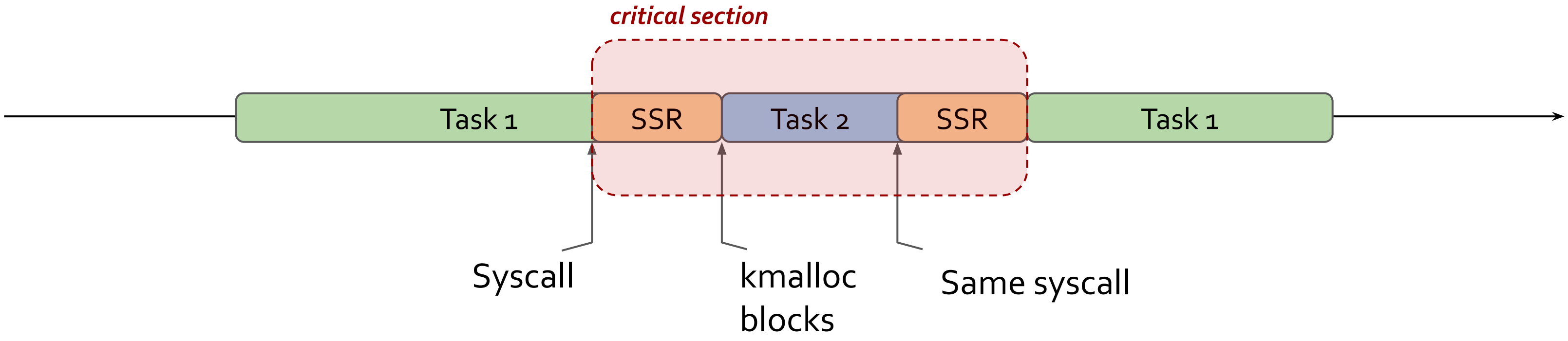

```
queue_t *shared_q;


my_irq_handler() {
    data = io(...);
    push(shared_q, data);
}
```

```
my_syscall() {
    n = length(shared_q);
    if(n > 0) {
        buf = kmalloc(1024);
        pop(shared_q, buf);
    }
}
```

When Synchronization is Necessary

System Calls and Interrupts




```
queue_t *shared_q;
```

```
my_syscall() {
    n = length(shared_q);
    if(n > 0) {
        buf = kmalloc(1024);
        pop(shared_q, buf);
    }
}
```

When Synchronization is not Necessary

We can recap some circumstances that do not require synchronization:

- critical parts of the interrupt handlers, which runs with interrupt disabled
- interrupt handlers, softirqs and tasklets are all non-preemptable
- a kernel control path performing interrupt handling cannot be interrupted by a kernel control path for running a deferrable function or a system call service routine
- softirqs and tasklets are not interleaved on a given CPU
- the same tasklet cannot be executed simultaneously on several CPUs

Therefore:

- code interrupt handlers and softirqs as reentrant functions
- use per-CPU variables in softirq and tasklets since they do not require synchronization
- a data structure used in only one kind of tasklet does not require synchronization

Primitives

We will now see how the kernel control path can be interleaved while avoiding race conditions among the shared data.

Table 5-2. Various types of synchronization techniques used by the kernel

Technique	Description	Scope
Per-CPU variables	Duplicate a data structure among the CPUs	All CPUs
Atomic operation	Atomic read-modify-write instruction to a counter	All CPUs
Memory barrier	Avoid instruction reordering	Local CPU or All CPUs
Spin lock	Lock with busy wait	All CPUs
Semaphore	Lock with blocking wait (sleep)	All CPUs
Seqlocks	Lock based on an access counter	All CPUs
Local interrupt disabling	Forbid interrupt handling on a single CPU	Local CPU
Local softirq disabling	Forbid deferrable function handling on a single CPU	Local CPU
Read-copy-update (RCU)	Lock-free access to shared data structures through pointers	All CPUs

Bovet, Daniel P., and Marco Cesati. *Understanding the Linux Kernel: from I/O ports to process management*. " O'Reilly Media, Inc.", 2005.

7.2.1

Per CPU-Variables

Per-CPU Variables

Explicit synchronization has a cost and if it can be avoided we gain in performances. The simplest technique for avoiding it is to declare per-CPU variables. Obviously they **do not protect** against asynchronous functions and preemption with reschedule on another core, therefore they can be used only in particular cases or even protected with other synchronization systems.

Table 5-3. Functions and macros for the per-CPU variables

Macro or function name	Description
`DEFINE_PER_CPU(type, name)`	Statically allocates a per-CPU array called `name` of `type` data structures
`per_cpu(name, cpu)`	Selects the element for CPU `cpu` of the per-CPU array `name`
`__get_cpu_var(name)`	Selects the local CPU's element of the per-CPU array `name`
`get_cpu_var(name)`	Disables kernel preemption, then selects the local CPU's element of the per-CPU array `name`
`put_cpu_var(name)`	Enables kernel preemption (`name` is not used)
`alloc_percpu(type)`	Dynamically allocates a per-CPU array of `type` data structures and returns its address
`free_percpu(pointer)`	Releases a dynamically allocated per-CPU array at address `pointer`
`per_cpu_ptr(pointer, cpu)`	Returns the address of the element for CPU `cpu` of the per-CPU array at address `pointer`

Bovet, Daniel P., and Marco Cesati. *Understanding the Linux Kernel: from I/O ports to process management*. " O'Reilly Media, Inc.", 2005.

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7. Concurrency in the Kernel

7.2 Synchronization

Atomic Operations

Atomic Operations

Several assembly instructions are of type “read-modify-write” (RMW), that is they access a memory location **twice**, the first time to read and the second to write a new value.

Suppose that two control path running on two CPUs try to RMW at the same memory location at the same time by using a non-atomic operations. Accessing are serialized by the chip, so when the first read has completed, the second reads the (old) value. Both the CPUs try to write the same (new) value and again accesses are serialized so both write are eventually executed. However, the global result is wrong.

To solve this problem we need to use instructions that are **atomic** at chip level. They the following.

Atomic Operations

Classification

In the 8086 architecture the we have:

- instructions that make zero or one aligned memory access, they **are atomic**
- RMW instructions (such `inc` or dec) **are atomic only** in a uniprocessor system
- RMW instructions prefixed by lock **are always atomic**, even on multiprocessor
- instructions prefixed by `rep` **are not atomic**

Since you cannot tell the compiler when to use atomic instructions the kernel defines different facilities.

Function	Description
`atomic_read(v)`	Return *v
`atomic_set(v,i)`	Set *v to i
`atomic_add(i,v)`	Add i to *v
`atomic_sub(i,v)`	Subtract i from *v
`atomic_sub_and_test(i, v)`	Subtract i from *v and return 1 if the result is zero; 0 otherwise
`atomic_inc(v)`	Add 1 to *v
`atomic_dec(v)`	Subtract 1 from *v
`atomic_dec_and_test(v)`	Subtract 1 from *v and return 1 if the result is zero; 0 otherwise
`atomic_inc_and_test(v)`	Add 1 to *v and return 1 if the result is zero; 0 otherwise
`atomic_add_negative(i, v)`	Add i to *v and return 1 if the result is negative; 0 otherwise
`atomic_inc_return(v)`	Add 1 to *v and return the new value of *v
`atomic_dec_return(v)`	Subtract 1 from *v and return the new value of *v
`atomic_add_return(i, v)`	Add i to *v and return the new value of *v
`atomic_sub_return(i, v)`	Subtract i from *v and return the new value of *v

Another class of atomic functions operate on bit masks (see Table 5-5).

Table 5-5. Atomic bit handling functions in Linux

Function	Description
`test_bit(nr, addr)`	Return the value of the nrth bit of *addr
`set_bit(nr, addr)`	Set the nrth bit of *addr
`clear_bit(nr, addr)`	Clear the nrth bit of *addr
`change_bit(nr, addr)`	Invert the nrth bit of *addr
`test_and_set_bit(nr, addr)`	Set the nrth bit of *addr and return its old value
`test_and_clear_bit(nr, addr)`	Clear the nrth bit of *addr and return its old value
`test_and_change_bit(nr, addr)`	Invert the nrth bit of *addr and return its old value
`atomic_clear_mask(mask, addr)`	Clear all bits of *addr specified by mask
`atomic_set_mask(mask, addr)`	Set all bits of *addr specified by mask

Bovet, Daniel P., and Marco Cesati. *Understanding the Linux Kernel: from I/O ports to process management*. " O'Reilly Media, Inc.", 2005.

7.2.3

7. Concurrency in the Kernel

7.2 Synchronization

Memory Barriers

Memory Barriers

Compilers may reorder assembly instructions differently from the C code for optimization reasons. However, when dealing with synchronization this mechanism must be avoided.

An *optimization barrier* primitive ensures that the assembly language instructions corresponding to C statements placed before the primitive are not mixed by the compiler with asm instructions corresponding to C statements placed after the primitive.

The macro `barrier()` expands to `asm` **`volatile`**`(“” ::: “`**`memory`**`”)`. This does not ensure that the asm instructions will not be mixed by the CPU. For this necessity we can define a **memory barrier**, that ensures that the operations placed before the primitive are finished before starting the operations placed after the primitive.

Memory Barriers

Instructions

In the 8086 architecture, the following instructions act as memory barriers:

- all instructions that operates on I/O ports (eg. `in`, `out`)
- all instructions prefixed by `lock`
- all instructions that write into control/system/debug registers (even `cli`, `sti`, etc.)
- `lfence`, `sfence`, and `mfence` implements read/write/rw memory barriers
- a few special assembly instructions, like `iret`

On the right the kernel facilities for using memory barriers.

Table 5-6. Memory barriers in Linux

Macro	Description
`mb()`	Memory barrier for MP and UP
`rmb()`	Read memory barrier for MP and UP
`wmb()`	Write memory barrier for MP and UP
`smp_mb()`	Memory barrier for MP only
`smp_rmb()`	Read memory barrier for MP only
`smp_wmb()`	Write memory barrier for MP only

Bovet, Daniel P., and Marco Cesati. *Understanding the Linux Kernel: from I/O ports to process management*. " O'Reilly Media, Inc.", 2005.

7.2.4

7. Concurrency in the Kernel

7.2 Synchronization

Spinlocks

Spinlocks

A widely used synchronization technique is locking. When a kernel thread needs to access to a critical region it must acquire a lock on it.

Spinlocks are a special kind of locks designed to work in a multiprocessor environment. If the kernel control path finds a lock open it acquires the lock and continues the execution, otherwise it "spins" around repeatedly **executing a instruction loop**. Therefore the kernel control path remains running on the CPU (and it can be preempted), kernel preemption is disabled during the critical region.

The Kernel API, on the right, is based on atomic operations.

Table 5-7. Spin lock macros

Macro	Description
`spin_lock_init()`	Set the spin lock to 1 (unlocked)
`spin_lock()`	Cycle until spin lock becomes 1 (unlocked), then set it to 0 (locked)
`spin_unlock()`	Set the spin lock to 1 (unlocked)
`spin_unlock_wait()`	Wait until the spin lock becomes 1 (unlocked)
`spin_is_locked()`	Return 0 if the spin lock is set to 1 (unlocked); 1 otherwise
`spin_trylock()`	Set the spin lock to 0 (locked), and return 1 if the previous value of the lock was 1; 0 otherwise

Bovet, Daniel P., and Marco Cesati. *Understanding the Linux Kernel: from I/O ports to process management*. " O'Reilly Media, Inc.", 2005.

Spinlocks

V5.11

APIs

```c
#include <linux/spinlock.h>

spinlock_t my_lock = SPINLOCK_UNLOCKED;
spin_lock_init(spinlock_t *lock);
spin_lock(spinlock_t *lock);
spin_lock_irqsave(spinlock_t *lock, unsigned long flags);
spin_lock_irq(spinlock_t *lock);
spin_lock_bh(spinlock_t *lock);
spin_unlock(spinlock_t *lock);
spin_unlock_irqrestore(spinlock_t *lock, unsigned long flags);
spin_unlock_irq(spinlock_t *lock);
spin_unlock_bh(spinlock_t *lock);
spin_is_locked(spinlock_t *lock);
spin_trylock(spinlock_t *lock)
spin_unlock_wait(spinlock_t *lock);
```

Spinlocks

V5.11

APIs

```c
static inline unsigned long __raw_spin_lock_irqsave(raw_spinlock_t *lock)
{
	unsigned long flags;

	local_irq_save(flags);
	preempt_disable();
	spin_acquire(&lock->dep_map, 0, 0, _RET_IP_);

	return flags;
}
```

https://elixir.bootlin.com/linux/v5.11/source/include/linux/spinlock_api_smp.h#L104

```c
static inline void __raw_spin_lock_irq(raw_spinlock_t *lock)
{
	local_irq_disable();
	preempt_disable();
	spin_acquire(&lock->dep_map, 0, 0, _RET_IP_);
	LOCK_CONTENDED(lock, do_raw_spin_trylock, do_raw_spin_lock);
}
```

https://elixir.bootlin.com/linux/v5.11/source/include/linux/spinlock_api_smp.h#L124

Read/Write Spinlocks

Read and write spinlocks have been introduced to increase the amount of concurrency inside the kernel. They allow several kernel control paths to simultaneously read the same data structure, as long as no kernel control path modifies it. For writing we need to acquire the write version of the lock.

```
rwlock_t xxx_lock = __RW_LOCK_UNLOCKED(xxx_lock);
unsigned long flags;

read_lock_irqsave(&xxx_lock, flags);
// critical section that only reads the info ...
read_unlock_irqrestore(&xxx_lock, flags);

write_lock_irqsave(&xxx_lock, flags);
// read and write exclusive access to the info ...
write_unlock_irqrestore(&xxx_lock, flags);
```

7.2.5

7. Concurrency in the Kernel

7.2 Synchronization

Seqlocks

Seqlocks

When using r/w spinlocks, requests issued by the kernel control path have all the same priority: readers must wait until the writer has finished and the vice versa.

Seqlocks are similar to r/w spinlocks, except that they give much higher priority to writers: a write can proceed even if readers are active. Therefore a writer **never waits** but a reader may be forced to read the same data until it gets a valid copy.

```
#include <linux/seqlock.h>

seqlock_t lock1 = SEQLOCK_UNLOCKED;
// or
seqlock_t lock2;
seqlock_init(&lock2);

write_seqlock(&the_lock);
/* Make changes here */
write_sequnlock(&the_lock);
```

Increases the sequence counter

Increases again, so while writing counter is odd otherwise even

Seqlocks

Readers do not acquire a lock but they check the sequence number.

Retrieve the sequence number

```
unsigned int seq;
do {
      seq = read_seqbegin(&the_lock);
      /* Make a copy of the data of interest */
} while read_seqretry(&the_lock, seq);
```

checks whether the initial number was odd and if it changed

7.2.6

7. Concurrency in the Kernel

7.2 Synchronization

RCU

Ready-Copy-Update

RCU is another synchronization technique designed to protect data structures that are mostly accessed for reading by several CPUs. RCU allows many readers and many writers to proceed concurrently (an improvement over seqlocks which allows only one writer to proceed) and it is **lock-free**. The keys idea consist of limiting the scope of RCU:

- only data structures that are dynamically allocated and referenced by means of pointer can be protected by RCU
- no kernel control path can sleep inside a critical region protected by RCU

In general, writers perform updates by creating new copy, readers read from the old copy therefore multiple copies allows readers and writers to read data concurrently. This is achieved with three fundamental mechanisms:

1. publish-subscribe for **insertion**
2. wait for pre-existing RCU readers to complete for **deletion**
3. maintain multiple versions of RCU-updated objects for **read**

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Insertion

```
struct foo {
    int a;
    int b;
    int c;
};
struct foo *gp = NULL;
/* . . . */
p = kmalloc(sizeof(*p), GFP_KERNEL);
p->a = 1;
p->b = 2;
p->c = 3;

gp = p;
```

Is this always correct?

https://slidetodoc.com/cs-510-concurrent-systems-jonathan-walpole-what-is/

Insertion

```c
struct foo {
     int a;
     int b;
     int c;
};
struct foo *gp = NULL;
/* . . . */
p = kmalloc(sizeof(*p), GFP_KERNEL);
p->a = 1;
p->b = 2;
p->c = 3;

rcu_assign_pointer(gp, p);
```

The "Publish-Subscribe".
The function prevents write side reordering that could break publishing

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Reading

```c
if (p != NULL) {
    do_something_with(p->a, p->b, p->c);
}
```

Is this always correct?

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Reading

```
rcu_read_lock();
p = rcu_dereference(gp);
if (p != NULL) {
    do_something_with(p->a, p->b, p->c);
}
rcu_read_unlock();
```

The function prevents read side reordering that could break publishing

Prevent memory reclamation - but do not prevent concurrent writing!

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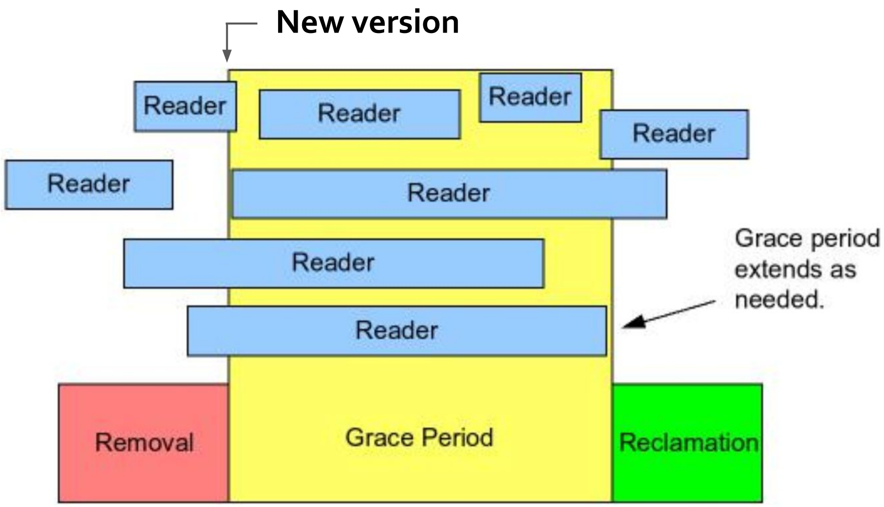
Deletion

Wait pre-existing RCU readers

But how long do we have to wait before its safe to reclaim an old version? Until all readers have finished reading? No, that's too strong! If new readers picked up a newer version we don't need to wait for them to finish - we just need to wait for **readers** who might be **reading** the **version** we want **to reclaim**.



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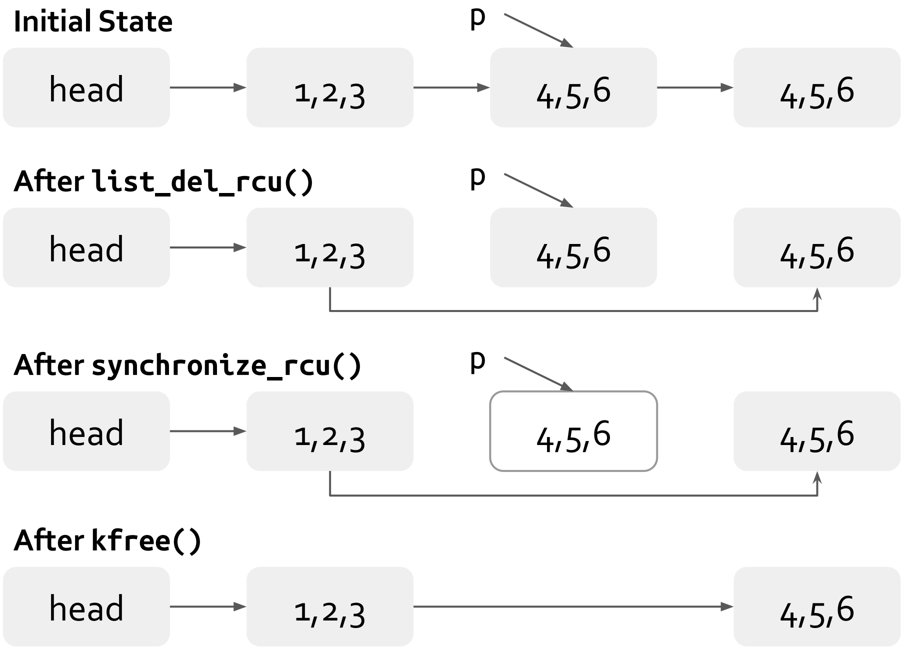
Deletion

```c
struct foo {
    struct list_head list;
    int a;
    int b;
    int c;
};
LIST_HEAD(head);
/* . . . */
p = search(head, key);
if (p != NULL) {
    list_del_rcu(&p->list);
    synchronize_rcu();
    kfree(p);
}
```

There are two functions for deferring deletion:

- synchronize_rcu() (synchronous)
- call_rcu() (asynchronous)



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Deletion

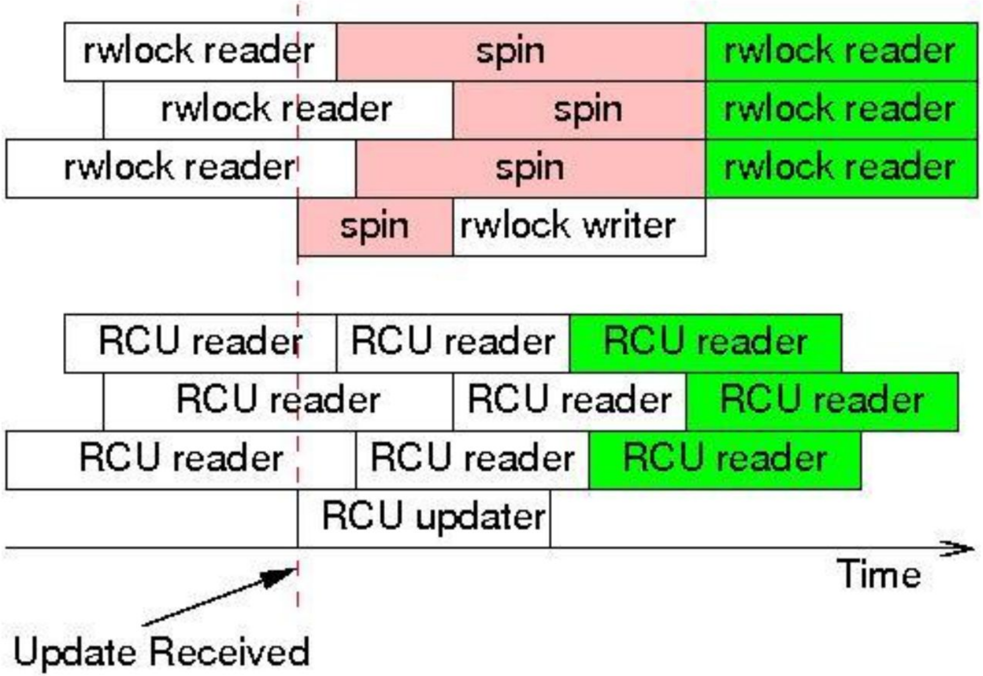
Garbage Collection

An old version of a data structure can be still accessed by readers. It can be freed only after that all readers have called `rcu_read_unlock()`.

A writer cannot waste to much time waiting for this condition, for this reason `call_rcu()` registers a callback function to free the old data structure.

Callbacks are activated by a dedicated SoftIRQ action (if you remember there was one with RCU in the name).

RCU vs RW Spinlocks



Semaphores

Semaphores

A semaphore implements a locking primitive that allows waiters to sleep until the desired resource becomes free. Linux offers two kinds of semaphores:

- **Kernel Semaphores**, which are used only by kernel control path
- System V IPC Semaphores, which are used by user space processes

We only focus on the formers here.

A kernel semaphore is similar to a spinlock in that it does not allow a control path to proceed unless the lock is open. However, differently from a spinlock when a kernel control path tries to acquire the lock the process is suspended. For this reason, semaphores can be used only within a **process context** (obv. Interrupt handlers and deferrable functions cannot use them).

Semaphores

API

`void sema_init(struct semaphore *sem, int val)`	Dynamically initialize a Semaphore
`int __must_check down_interruptible(struct semaphore *sem);`	Acquire Semaphore, decrement count and set task to TASK_INTERRUPTIBLE state
`int __must_check down_killable(struct semaphore *sem);`	Acquire Semaphore, decrement count and set task to TASK_KILLABLE state
`int __must_check down_trylock(struct semaphore *sem);`	Try and acquire the Semaphore, if lock is unavailable – do not wait for lock to be acquired
`int __must_check down_timeout(struct semaphore *sem, long jiffies);`	Try to acquire the Semaphore and exit if timeout expires
`void down(struct semaphore *sem);`	Acquire a Semaphore
`void up(struct semaphore *sem);`	Release a Semaphore

Read/Write Semaphores

Read/Write semaphores are exactly like the spinlock counterpart but the process is allowed to sleep.

API

- `void down_read(struct rw_semaphore *sem)` - lock for reading;
- `int down_read_trylock(struct rw_semaphore *sem)` - try lock for reading;
- `void down_write(struct rw_semaphore *sem)` - lock for writing;
- `int down_write_trylock(struct rw_semaphore *sem)` - try lock for writing;
- `void up_read(struct rw_semaphore *sem)` - release a read lock;
- `void up_write(struct rw_semaphore *sem)` - release a write lock;

Advanced Operating Systems and Virtualization

[7] Concurrency in the Kernel

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