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Advanced Operating Systems

#2

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Introduction of Myself

- Name: Hiroyuki Chishiro
- Project Lecturer at Kato Laboratory in December 2017 - Present.

- Short Bibliography
  - Ph.D. at Keio University on March 2012 (Yamasaki Laboratory: Same as Prof. Kato).
  - JSPS Research Fellow (PD) in April 2012 – March 2014.
  - Research Associate at Keio University in April 2014 – March 2016.
  - Assistant Professor at Advanced Institute of Industrial Technology in April 2016 – November 2017.
- Research Interests
  - Real-Time Systems
  - Operating Systems
  - Middleware
  - Trading Systems

Course Plan

- Multi-core Resource Management
- Many-core Resource Management
- GPU Resource Management
- Virtual Machines
- Distributed File Systems
- High-performance Networking
- Memory Management
- Network on a Chip
- Embedded Real-time OS
- Device Drivers
- Linux Kernel

Schedule

1. 2018.9.28 Introduction + Linux Kernel (Kato)
2. 2018.10.5 Linux Kernel (Chishiro)
3. 2018.10.12 Linux Kernel (Kato)
4. 2018.10.19 Linux Kernel (Kato)
5. 2018.10.26 Linux Kernel (Kato)
6. 2018.11.2 Advanced Research (Chishiro)
7. 2018.11.9 Advanced Research (Chishiro)
8. 2018.11.16 (No Class)
9. 2018.11.23 (Holiday)
10. 2018.11.30 Advanced Research (Kato)
11. 2018.12.7 Advanced Research (Kato)
12. 2018.12.14 Advanced Research (Chishiro)
13. 2018.12.21 Linux Kernel
14. 2019.1.11 Linux Kernel
15. 2019.1.18 (No Class)
16. 2019.1.25 (No Class)

Linux Kernel

Introducing Synchronization

/* The cases for Linux */

Acknowledgement:

Prof. Pierre Olivier, ECE 4984, Linux Kernel Programming, Virginia Tech

Outline

- Introduction
- Atomic Operations
- Spin Locks
- Semaphores and Mutexes
- Other Synchronization Mechanisms
- Ordering and Memory Barriers

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Critical Regions and Race Conditions

- The kernel is programmed using the shared memory model.
  - **Shared data must be protected against concurrent access.**
    - Interruption/preemption on a single core
    - Pure concurrent access on a multi-core CPU (SMP)
- **Critical region/section**: part of the code manipulating shared data
  - must execute atomically, i.e. without interruption
  - should not be executed in parallel on SMP
- **Race condition**: two threads concurrently executing the same critical region
  - It’s a bug!

Critical Regions and Race Conditions

- Why Protecting Shared Data?
  - Example: ATM

```
int total = get_total_from_account(); /* total funds in user account */
int withdrawal = get_withdrawal_amount(); /* amount user asked to withdrawal */
/* check whether the user has enough funds in her account */
if (total < withdrawal) {
	error("Not enough money!");
	return -1;
}

/* The user has enough money, deduct the withdrawal amount from here total */
total -= withdrawal;
update_total_funds(total);

/* give the money to the user */
spit_out_money(withdrawal);
```

Critical Regions and Race Conditions (2)

- Assume two transactions are happening nearly at the same time
  - Example: shared credit card account
- Assume
  - total == 105
  - withdrawal1 == 100
  - withdrawal2 == 10
    - Should fail as !(100+10 > 105)

```
int total = get_total_from_account();
int withdrawal = get_withdrawal_amount();

if (total < withdrawal) {
        error("Not enough money!");
        return -1;
}

total -= withdrawal;
update_total_funds(total);
spit_out_money(withdrawal);
```

Critical Regions and Race Conditions (3)

- Assume:
  - total == 105, withdrawal1 == 100,
  - withdrawal2 == 10
- Possible scenario:
  - Threads check that 100 < 105 and 10 < 105
    - All good
  - 2 Thread 1 updates
    - total = 105 - 100 = 5
  - 3 Thread 2 updates
    - total = 105 - 10 = 95
- **Total withdrawal: 110, and there is 95 left on the account!**

```
int total = get_total_from_account();
int withdrawal = get_withdrawal_amount();

if (total < withdrawal) {
        error("Not enough money!");
        return -1;
}

total -= withdrawal;
update_total_funds(total);
spit_out_money(withdrawal);
```

Critical Regions and Race Conditions: Single Variable Example

- Consider this C instruction: i++;
  - It might translate into machine code as:

> - get the current value of i and copy it into a register.
> - add one to the value stored into the register.
> - write back to memory the new value of i.

- Assume i == 7 is shared between two threads, both wanting to increment it:

Thread 1	Thread 2
get i(7)	-
increment i(7->8)	-
write back i(8)	-
-	get i(8)
-	increment i(8 -> 9)
-	write back i(9)

Time

Critical Regions and Race Conditions: Single Variable Example (2)

- Race Condition:

Thread 1	Thread 2
get i(7)	get i(7)
increment i(7->8)	-
-	increment i(7->8)
write back i(8)	-
-	write back i(8)

Time

Problem!

Critical Regions and Race Conditions: Single Variable Example (3)

- A solution is to use **atomic instructions**
  - Instructions provided by the CPU that cannot **interleave**
  - Example: get, increment, and store

Time

Thread 1	Thread 2
get, increment, and store i(7->8)	-
-	get, increment, and store i(8->9)

- Or

Time

Thread 1	Thread 2
-	get, increment, and store i(7->8)
get, increment, and store i(8->9)	-

Locking

- Atomic operations are not sufficient for protecting shared data in long and complex critical regions
  - Example: a shared stack (data structure) with multiple pushing and popping threads
- Need a mechanism to assure **a critical region is executed atomically by only one core at the same time → locks**.

Locking (2)

- Example - stack protected by a lock:

Thread 1	Thread 2
try to lock the stack	try to lock the stack
success: lock acquired	failure: waiting…
access stack…	waiting…
unlock the stack…	waiting…
…	success: lock acquired
…	access stack
…	unlock the stack

Time

- Locking is implemented by the programmer *voluntarily (own willing)*
  - No indication from the compiler!
  - No protection generally ends up in data corruption
  - → inconsistent behavior for the program
  - → **difficult to debug and trace back the source of the issue**
- Locking/unlocking primitives are implemented through atomic operations

Causes of Concurrency

- From a single core standpoint: **interleaving asynchronous execution threads**
  - Example: preemption or interrupts
  - **pseudo-concurrency**
- On a multi-core: **true concurrency**
- **Sources of concurrency in the kernel:**
  - Interrupts
  - Softirqs
  - Kernel preemption
  - Sleeping and synchronization
  - Symmetrical multiprocessing
- Need to understand and prepare for these: **identifying shared data and related critical regions**
  - Needs to be done **from the start as concurrency bugs are difficult to detect and solve**

Causes of Concurrency (2)

- Naming:
  - Code safe from access from an interrupt handler: **interrupt-safe**
  - This code can be interrupted by an interrupt handler and this will not cause any issue
- Code safe from access from multiple cores: **SMP-safe**
  - This code can be executed on multiple cores at the same time without issue
- Code safe from concurrency with kernel preemption: **preempt-safe**
  - This code can be preempted without issue

What to Protect?

- When writing some code, **observe the data manipulated by the code**
  - ***If anyone else (thread/handler) can see it, lock it.***
- Questions to ask when writing kernel code:
  - Are the data global?
  - Are the data shared between process and interrupt context?
  - If the process is preempted while accessing the data, can the newly scheduled process access the same data?
  - Can the code blocks on anything? If so, in what state does that leave any shared data?
  - What prevents the data from being freed out from under me?
  - What happens if this function is called again on another core?

Deadlocks

- Situations in which one or several threads are waiting on locks for one or several resources that will never be freed → they are stuck
  - Real-life example: traffic deadlock
  - Self-deadlock (1 thread):

```
acquire lock
acquire lock again
waiting indefinitely ...
```

  - Deadly embrace (n threads and n locks):

Thread 1	Thread 2
acquire lock A	acquire lock B
try to acquire lock B	try to acquire lock A
wait for lock B...	wait for lock A...

Time

Deadlocks: How to Prevent Them

- Implement **lock ordering**
  - Nested lock must always be obtained in the same order
  - Document lock usage in comments

Thread 1	Thread 2
acquire lock cat	acquire lock fox
acquire lock dog	try to acquire lock dog
try to acquire lock fox	wait for lock dog...
wait for lock fox...	wait for lock dog...

Time

- **Do not double-acquire the same lock**

Contention and Scalability

- A lock is said to be **contented** when there are often threads waiting for it.
- A highly contented lock can become a bottleneck for the system performance.
- **Coarse vs fine-grained locking**
  - Coarse lock example: protecting an entire subsystem’s shared data structures
    - Simple Implementation
    - Low Scalability
  - Fine-grained locks:
    - Complex Implementation
    - High Scalability
- Start simple and grow in complexity if needed

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- Spin Locks
- Semaphores and Mutexes
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Atomic Operations

- perform (simple) operations in memory and either succeed or fail in their entirety
  - Regardless of what operations are executed on other cores
  - Without interruption
- Examples:
  - Fetch-and-add: does atomic increment.
  - Test-and-set: sets a value at a memory location and returns the previous value.
  - Compare-and-swap: modifies the content of a memory location only if the previous content is equal to a given value.
- Linux provides two APIs:
  - Integers atomic operations
  - Bitwise atomic operations

Atomic Integer Operations

- include/linux/types.h:

```
typedef struct {
        int counter;
} atomic_t;
```

- API defined in include/asm/atomic.h
- Usage:

```
atomic_t v; /* define v */
atomic_t u = ATOMIC_INIT(0); /* define and initialize u to 0 */

atomic_set(&v, 4); /* v = 4 (atomically) */
atomic_add(2, &v); /* v = v + 2 == 6 (atomically) */
atomic_inc(&v); /* v = v + 1 == 7 (atomically) */
```

Atomic Integer Operations API

Atomic Integer Operation	Description
ATOMIC_INIT(i)	Declare and initialize to i
int atomic_read(atomic_t *v)	Atomically read the value of v
void atomic_set(atomic_t *v, int i)	Atomically set v to i
void atomic_add(int i, atomic_t *v)	Atomically add i to v
void atomic_sub(int i, atomic_t *v)	Atomically subtract i from v
void atomic_inc(atomic_t *v)	Atomically add 1 to v
void atomic_dec(atomic_t *v)	Atomically subtract 1 from v
int atomic_sub_and_test(int i, atomic_t *v)	Atomically subtract i from v and return true if the result is zero, otherwise false
int atomic_add_negative(int i, atomic_t *v)	Atomically add i to v and return true if the result is negative, otherwise false

Atomic Integer Operations API (2)

Atomic Integer Operation	Description
int atomic_add_return(int i, atomic_t *v)	Atomically add i to v and return the result
int atomic_sub_return(int i, atomic_t *v)	Atomically subtract i from v and return the result
int atomic_inc_return(atomic_t *v)	Atomically increment v by 1 and return the result
int atomic_dec_return(atomic_t *v)	Atomically decrement v by 1 and return the result
int atomic_dec_and_test(atomic_t *v)	Atomically decrement v by 1 and return true if the result is zero, false otherwise
int atomic_inc_and_test(atomic_t *v)	Atomically increment v by 1 and return true if the result is zero, false otherwise

64-bits Atomic Operations API

Atomic Integer Operation	Description
ATOMIC64_INIT(i)	Declare and initialize to i
int atomic64_read(atomic_t *v)	Atomically read the value of v
void atomic64_set(atomic_t *v, int i)	Atomically set v to i
void atomic64_add(int i, atomic_t *v)	Atomically add i to v
void atomic64_sub(int i, atomic_t *v)	Atomically subtract i from v
void atomic64_inc(atomic_t *v)	Atomically add 1 to v
void atomic64_dec(atomic_t *v)	Atomically subtract 1 from v
int atomic64_sub_and_test(int i, atomic_t *v)	Atomically subtract i from v and return true if the result is zero, otherwise false
int atomic64_add_negative(int i, atomic_t *v)	Atomically add i to v and return true if the result is negative, otherwise false

64-bits Atomic Operations API (2)

Atomic Integer Operation	Description
int atomic64_add_return(int i, atomic_t *v)	Atomically add i to v and return the result
int atomic64_sub_return(int i, atomic_t *v)	Atomically subtract i from v and return the result
int atomic64_inc_return(atomic_t *v)	Atomically increment v by 1 and return the result
int atomic64_dec_return(atomic_t *v)	Atomically decrement v by 1 and return the result
int atomic64_dec_and_test(atomic_t *v)	Atomically decrement v by 1 and return true if the result is zero, false otherwise
int atomic64_inc_and_test(atomic_t *v)	Atomically increment v by 1 and return true if the result is zero, false otherwise

Atomic Integer Operations: Usage Example

```
#include <linux/module.h>
#include <linux/kernel.h>
#include <linux/init.h>
#include <linux/slab.h>
#include <linux/delay.h>
#include <linux/kthread.h>
#include <linux/sched.h>
#include <linux/types.h>

#define PRINT_PREF "[SYNC_ATOMIC] "
atomic_t counter; /* shared data: */
struct task_struct *read_thread, *write_thread;

static int writer_function(void *data)
{
        while (!kthread_should_stop()) {
                atomic_inc(&counter);
                msleep(500);
        }
        do_exit(0);
}
```

```
static int read_function(void *data)
{
        while (!kthread_should_stop()) {
                printk(PRINT_PREF "counter: %d¥n", atomic_read(&counter));
                msleep(500);
        }
        do_exit(0);
}

static int __init my_mod_init(void)
{
        printk(PRINT_PREF "Entering module.¥n");

        atomic_set(&counter, 0);
        read_thread = kthread_run(read_function, NULL, "read-thread");
        write_thread = kthread_run(writer_function, NULL, "write-thread");

        return 0;
}
static void __exit my_mod_exit(void)
{
        kthread_stop(read_thread);
        kthread_stop(write_thread);
        printk(KERN_INFO "Exiting module.¥n");
}

module_init(my_mod_init);
module_exit(my_mod_exit);
MODULE_LICENSE("GPL");
```

Atomic Bitwise Operations

- Atomic bitwise operations (include/linux/bitops.h)
- API functions operate on generic pointers (void *)
    - Example with long on 32-bits systems:
    - Bit 31 is the most significant bit
    - Bit 0 is the least significant bit

```
unsigned long word = 0; /* 32 / 64 bits according to the system */

set_bit(0, &word); /* bit zero is set atomically */
set_bit(1, &word); /* bit one is set atomically */
printk("&ul¥n", word); /* print "3" */
clear_bit(1, &word); /* bit one is unset atomically */
change_bit(0, &word); /* flip bit zero atomically (now unset) */

/* set bit as zero and return its previous value (atomically) */
if (test_and_set_bit(0, &word)) {
        /* not true in the case of our example */
}
/* you can mix atomic bit operations and normal C */
word = 7;
```

Atomic Bitwise Operations: API

Atomic Bitwise Operation	Description
void set_bit(int nr, void *addr)	Atomically set the nr-th bit starting from addr
void clear_bit(int nr, void *addr)	Atomically clear the nr-th bit starting from addr
void change_bit(int nr, void *addr)	Atomically flip the nr-th bit starting from addr
void test_and_set_bit(int nr, void *addr)	Atomically set the nr-th bit starting from addr and return the previous value
int test_and_clear_bit(int nr, void *addr)	Atomically clear the nr-th bit starting from addr and return the previous value

Atomic Bitwise Operations: API (2)

Atomic Bitwise Operation	Description
int test_and_change_bit(int nr, void *addr)	Atomically flip the nr-th bit starting from addr and return the previous value
int test_bit(int nr, void *addr)	Atomically return the value of the nr-th bit starting from addr

- Non-atomic bitwise operations (can be slightly faster according to the architecture) , prefixed with ' __'
  - Example: __test_bit()

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Spin Locks

- The most common lock used in the kernel: **spin lock**
- Can be **held by at most one thread of execution**
- When a thread tries to acquire an already held lock:
  - **Active waiting** (spinning)
    - Hurts performance when spinning for too long
    - However spinlocks are needed in context where one cannot sleep (interrupt)
  - As opposed to putting the thread to sleep (semaphores/mutexes)
- **In process context, do not sleep while holding a spinlock**
  - Another thread trying to acquire the spinlock hangs the CPU, preventing you to wake up
    - Deadlock

Usage

- API in include/linux/spinlock.h

```
DEFINE_SPINLOCK(my_lock);

spin_lock(&my_lock);
/* critical region */
spin_unlock(&my_lock);
```

- Lock/unlock methods disable/enable kernel preemption and acquire/release the lock
- spin_lock() is not recursive!
  - A thread calling spin_lock() twice on the same lock self-deadlocks
- Lock is compiled away on uniprocessor systems
  - Still needs do disabled/re-enable preemption

Usage: Interrupt Handlers

- Spin locks do not sleep: it is safe to use them in interrupt context
- **In an interrupt handler, need to disable local interrupts before taking the lock!**
  - Otherwise, risk of deadlock if interrupted by another handler accessing the same lock

```
DEFINE_SPINLOCK(my_lock); /* the spin lock */
unsigned long flags; /* to save the interrupt state */

spin_lock_irqsave(&my_lock, flags);
/* critical region */
spin_unlock_irqrestore(&my_lock, flags);
```

  - If it is known that interrupts are initially enabled:

```
spin_lock_irq(&my_lock);
/* critical region */
spin_unlock_irq(&my_lock);
```

  - Also true (need to disable local interrupts) for process context to share data with interrupt handler
- Debugging spin locks: CONFIG_DEBUG_SPINLOCKS [2], CONFIG_DEBUG_LOCK_ALLOC [1]

Other Spin Locks Methods

Method	Description
spin_lock()	Acquire a lock
spin_lock_irq()	Disable local interrupts and acquire a lock
spin_lock_irqsave()	Save current state of local interrupts, disable local interrupts, and acquire a lock
spin_unlock()	Release a lock
spin_unlock_irq()	Release a lock and enable local interrupts
spin_unlock_irqrestore()	Release a lock and reset interrupts to previous state
spin_lock_init()	Dynamically initialize a spinlock_t
spin_trylock()	Try to acquire a lock and directly returns zero if unavailable
spin_is_locked()	Return non-zero if the lock is currently acquired, otherwise return zero

Spin Locks and Bottom Halves

- spin_lock_bh()/spin_unlock_bh():
  - Disable softirqs before taking the lock
- In process context:
  - Data shared with bottom-half context?
    - Disable bottom-halves + lock
  - Data shared with interrupt handler?
    - Disable interrupts + lock

Usage Example

```
#include <linux/module.h>
#include <linux/kernel.h>
#include <linux/init.h>
#include <linux/slab.h>
#include <linux/delay.h>
#include <linux/spinlock.h>
#include <linux/kthread.h>
#include <linux/sched.h>

#define PRINT_PREF "[SYNC_SPINLOCK] "

unsigned int counter; /* shared data: */
DEFINE_SPINLOCK(counter_lock);
struct task_struct *read_thread, *write_thread;

static int writer_function(void *data)
 {
	while (!kthread_should_stop()) {
		spin_lock(&counter_lock);
		counter++;
		spin_unlock(&counter_lock);
		msleep(500);
	}
	do_exit(0);
}
```

```
static int read_function(void *data)
 {
	while (!kthread_should_stop()) {
		spin_lock(&counter_lock);
		printk(PRINT_PREF "counter: %d¥n", counter);
		spin_unlock(&counter_lock);
		msleep(500);
	}
	do_exit(0);
}

static int __init my_mod_init(void)
 {
	printk(PRINT_PREF "Entering module.¥n");
	counter = 0;

	read_thread = kthread_run(read_function, NULL, "read-thread");
	write_thread = kthread_run(writer_function, NULL, "write-thread");

	return 0;
}
static void __exit my_mod_exit(void)
 {
	kthread_stop(read_thread);
	kthread_stop(write_thread);
	printk(KERN_INFO "Exiting module.¥n");
}

module_init(my_mod_init);
module_exit(my_mod_exit);
MODULE_LICENSE("GPL");
```

Reader-Writer Spin Locks

- When entities accessing shared data can be clearly divided into readers and writers
- Example: list updated (write) and searched (read)
  - When updated, no other entity should update nor search
  - When searched, no other entity should update
  - **Safe to allow multiple readers in parallel**

```
DEFINE_RWLOCK(my_rwlock);      /* declaration & initialization */
```

- Reader code:

```
read_lock(&my_rwlock);
/* critical region */
read_unlock(&my_rwlock);
```

Writer code:

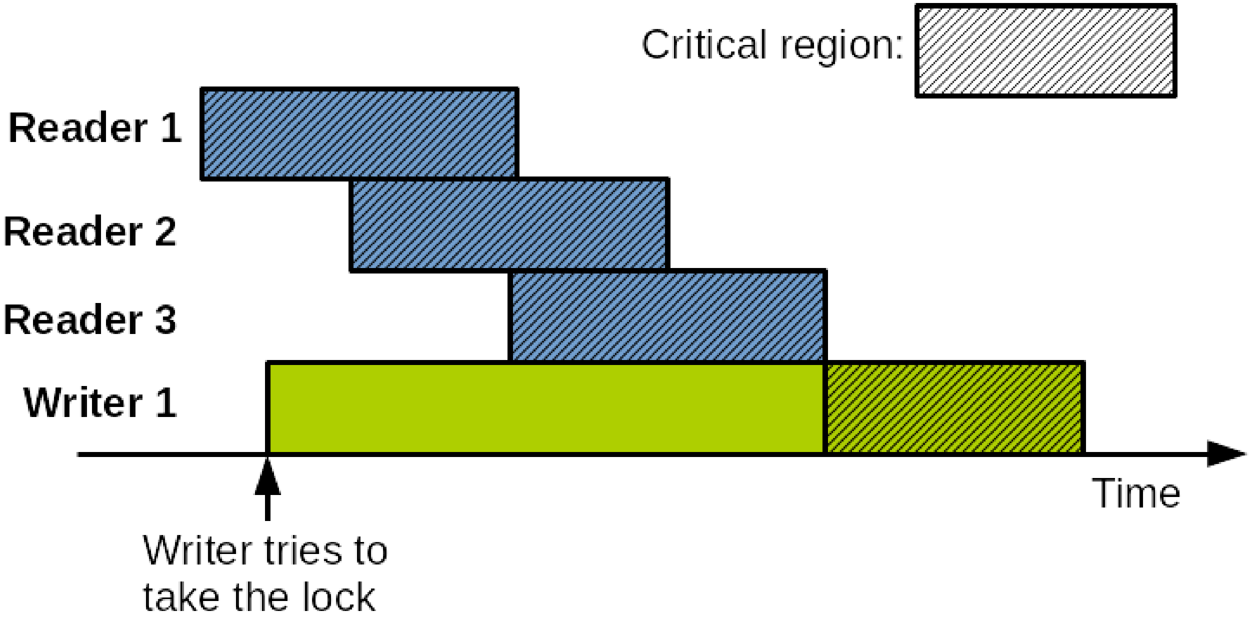
```
write_lock(&my_rwlock);
/* critical region */
write_unlock(&my_rwlock);
```

Reader-Writer Spin Locks (2)

- Deadlock

```
read_lock(&my_rwlock);
write_lock(&my_rwlock);
```

- **RW spinlocks favor readers over writers:**



Reader-Writer Spin Locks: Methods

- read_lock()
- read_lock_irq()
- read_lock_irqsave()
- read_unlock()
- read_unlock_irq()
- read_unlock_irqrestore()
- write_lock()
- write_lock_irq()
- write_lock_irqsave()
- write_unlock()
- write_unlock_irq()
- write_unlock_irqrestore()
- write_trylock()
- rwlock_init()

Reader-Writer Spin Locks: Usage Example

```
#include <linux/module.h>
#include <linux/kernel.h>
#include <linux/init.h>
#include <linux/slab.h>
#include <linux/delay.h>
#include <linux/spinlock.h>
#include <linux/kthread.h>
#include <linux/sched.h>

#define PRINT_PREF "[SYNC_RWSPINLOCK] "

unsigned int counter; /* shared data: */
DEFINE_RWLOCK(counter_lock);
struct task_struct *read_thread1, *read_thread2,
*read_thread3, *write_thread;

static int writer_function(void *data)
 {
        while (!kthread_should_stop()) {
                write_lock(&counter_lock);
                counter++;
                write_unlock(&counter_lock);
                msleep(500);
        }
        do_exit(0);
}
```

```
static int read_function(void *data)
 {
        while (!kthread_should_stop()) {
                read_lock(&counter_lock);
                printk(PRINT_PREF "counter: %d¥n", counter);
                read_unlock(&counter_lock);
                msleep(500);
        }
        do_exit(0);
}

static int __init my_mod_init(void)
 {
        printk(PRINT_PREF "Entering module.¥n");
        counter = 0;
        read_thread1 = kthread_run(read_function, NULL, "read-thread1");
        read_thread2 = kthread_run(read_function, NULL, "read-thread2");
        read_thread3 = kthread_run(read_function, NULL, "read-thread3");
        write_thread = kthread_run(writer_function, NULL, "write-thread");
        return 0;
}
```

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Semaphores Presentation

- **Semaphores: sleeping locks**
  - A thread trying to acquire an already held lock is put on a waitqueue.
  - When the semaphore becomes available, one task on the waitqueue is awaken.
- Well suited towards locks held for a long time
  - On the contrary, large overhead for locks held for short periods
- **No usable in interrupt context**
- A thread can sleep while holding a semaphore.
  - Another thread trying to acquire it will sleep and let you continue.
- A thread cannot hold a spinlock while trying to acquire a semaphore.
  - Might sleep!

Counting vs Binary Semaphores

- Contrary to spin locks, semaphores allow multiples holders.
- Counter initialized to a given value
  - Decremented each time a thread acquires the semaphore
  - The semaphore becomes unavailable when the counter reaches 0.
- In the kernel, most of the semaphores used are **binary semaphores**
  - Counter initialized to:
    - 1 -> initially available
    - 0 -> initially disabled

Semaphores Usage

- API in include/linux/semaphore.h

```
struct semaphore *sem1;

sem1 = kmalloc(sizeof(struct semaphore),
GFP_KERNEL);
if (!sem1)
        return -1;
/* counter == 1: binary semaphore */
sema_init(&sema, 1);

down(sem1);
/* critical region */
up(sem1);
```

```
/* Binary semaphore static declaration */
DECLARE_MUTEX(sem2);

if (down_interruptible(&sem2)) {
        /* signal received, semaphore not acquired */
}

/* critical region */
up(sem2);
```

- down() puts the thread to sleep in TASK_UNINTERRUPTIBLE mode.
- down_interruptible() uses TASK_INTERRUPTIBLE mode.

Semaphores Usage: Methods

- sema_init(struct semaphore *, int)
  - initializes the dynamically created semaphore with the given count
- init_MUTEX(struct semaphore *)
  - initializes the dynamically created semaphore with the count of 1
- init_MUTEX_LOCKED(struct semaphore *)
  - initializes the dynamically created semaphore with the count of 0
- down_interruptible(struct semaphore *)
  - tries to acquire the semaphore and goes into interruptible sleep if it is not available
- down(struct semaphore *)
  - tries to acquire the semaphore and goes into uninterruptible sleep if it is not available
    - **Deprecated** → prefer the use of down interruptible

Semaphores Usage (2)

- down_trylock(struct semaphore *)
  - tries to acquire the semaphore and immediately returns 0 if acquired, otherwise 1
- down_timeout(struct semaphore *, long timeout)
  - tries to acquire the semaphore and goes to sleep if not available. If the semaphore is not released after timeout jiffies, returns -ETIME
- up(struct semaphore *)
  - releases the semaphore and wakes up a waiting thread if needed

Reader-Writer Semaphores

- Example

```
DECLARE_RWSEM(rwsem1);

init_rwsem(&rwsem1);
down_read(rwsem1);
/* critical (read) region */
up_read(&rwsem1);
```

```
struct rw_semaphore *rwsem2;
rwsem2 = kmalloc(sizeof(struct rw_semaphore),
GFP_KERNEL);
if (!rwsem2)
        return -1;
init_rwsem(rwsem2);
down_write(rwsem2);
/* critical (write) region */
up_write(rwsem2);
```

Reader-Writer Semaphore Usage Example

- downgrade_write()
  - Convert an acquired write lock to a read one

```
#include <linux/module.h>
#include <linux/kernel.h>
#include <linux/init.h>
#include <linux/slab.h>
#include <linux/delay.h>
#include <linux/kthread.h>
#include <linux/sched.h>
#include <linux/rwsem.h>

#define PRINT_PREF "[SYNC_SEM] "

/* shared data: */
unsigned int counter;
struct rw_semaphore *counter_rwsemaphore;

struct task_struct *read_thread, *read_thread2, *write_thread;
static int writer_function(void *data)
 {
        while (!kthread_should_stop()) {
                down_write(counter_rwsemaphore);
                counter++;
```

```
                downgrade_write(counter_rwsemaphore);
                printk(PRINT_PREF "(writer) counter: %d¥n", counter);

                up_read(counter_rwsemaphore);
                msleep(500);
        }

        do_exit(0);
}

static int read_function(void *data)
 {
        while (!kthread_should_stop()) {
                down_read(counter_rwsemaphore);
                printk(PRINT_PREF "counter: %d¥n", counter);
                up_read(counter_rwsemaphore);
                msleep(500);
        }
        do_exit(0);
}
```

Reader-Writer Semaphore Usage Example (2)

```
static int __init my_mod_init(void)
{
        printk(PRINT_PREF "Entering module.¥n");
        counter = 0;

        counter_rwsemaphore = kmalloc(sizeof(struct rw_semaphore), GFP_KERNEL);
        if (!counter_rwsemaphore)
                return -1;

        init_rwsem(counter_rwsemaphore);
        read_thread = kthread_run(read_function, NULL, "read-thread");
        read_thread2 = kthread_run(read_function, NULL, "read-thread2");
        write_thread = kthread_run(writer_function, NULL, "write-thread");
        return 0;
}
```

```
static void __exit my_mod_exit(void)
{
        kthread_stop(read_thread);
        kthread_stop(write_thread);
        kthread_stop(read_thread2);

        kfree(counter_rwsemaphore);
        printk(KERN_INFO "Exiting module.¥n");
}

module_init(my_mod_init);
module_exit(my_mod_exit);
MODULE_LICENSE("GPL");
```

Mutexes

- are binary semaphore with stricter use cases:
  - Only one thread can hold the mutex at a time.
  - A thread locking a mutex must unlock it.
  - No recursive lock and unlock operations.
  - A thread cannot exit while holding a mutex.
  - A mutex cannot be acquired in interrupt context.
  - A mutex can be managed only through the API.
- With special debugging mode: (CONFIG_DEBUG_MUTEXES)
  - **The kernel can check and warn if these constraints are not met.**
- Mutex vs semaphore use?
  - If these constraints disallow the use of mutexes, use semaphores.
    - **Otherwise always use mutexes.**

Mutexes: Usage

- API in include/linux/mutex.h

```
DEFINE_MUTEX(mut1); /* static */

struct mutex *mut2 = kmalloc(sizeof(struct mutex), GFP_KERNEL); /* dynamic */
if (!mut2)
	return -1;
mutex_init(mut2);
mutex_lock(&mut1);
/* critical region */
mutex_unlock(&mut1);
```

Mutexes: Usage Example

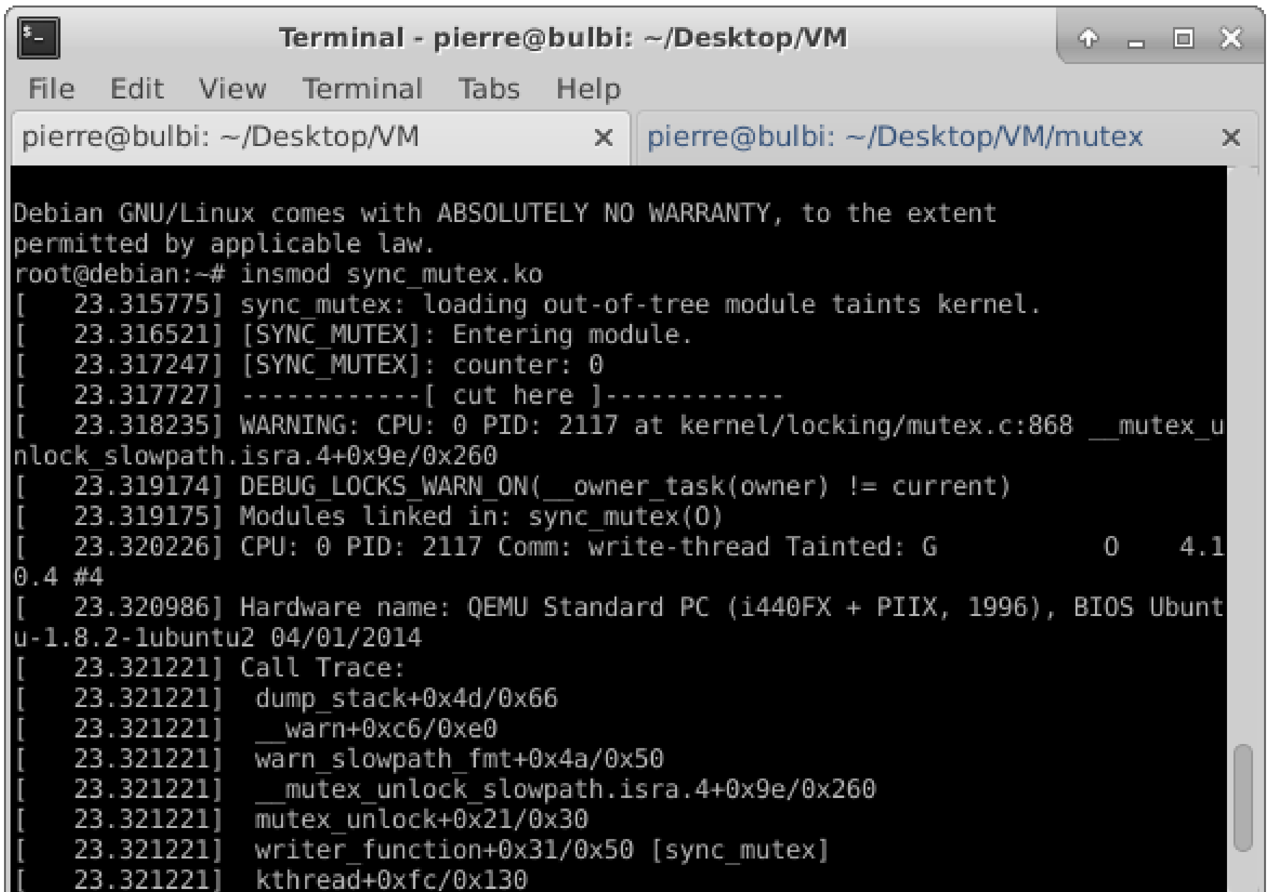
```
#include <linux/module.h>
#include <linux/kernel.h>
#include <linux/init.h>
#include <linux/slab.h>
#include <linux/delay.h>
#include <linux/kthread.h>
#include <linux/sched.h>
#include <linux/mutex.h>

#define PRINT_PREF "[SYNC_MUTEX]: "
/* shared data: */
unsigned int counter;
struct mutex *mut;
struct task_struct *read_thread, *write_thread;

static int writer_function(void *data)
 {
        while (!kthread_should_stop()) {
                mutex_lock(mut);
                counter++;
                mutex_unlock(mut);
                msleep(500);
        }
        do_exit(0);
}
```

```
static int read_function(void *data)
{
        while (!kthread_should_stop()) {
                mutex_lock(mut);
                printk(PRINT_PREF "counter: %d¥n", counter);
                mutex_unlock(mut);
                msleep(500);
        }

        do_exit(0);
}
```

```c
static int __init my_mod_init(void)
 {
        printk(PRINT_PREF "Entering module.¥n");
        counter = 0;

        mut = kmalloc(sizeof(struct mutex), GFP_KERNEL);
        if (!mut)
                return -1;
        mutex_init(mut);
        read_thread = kthread_run(read_function, NULL, "read-thread");
        write_thread = kthread_run(writer_function, NULL, "write-thread");

        return 0;
}

static void __exit my_mod_exit(void)
 {
        kthread_stop(read_thread);
        kthread_stop(write_thread);
        kfree(mut);
        printk(KERN_INFO "Exiting module.¥n");
}

module_init(my_mod_init);
module_exit(my_mod_exit);
MODULE_LICENSE("GPL");
```

Mutexes: Usage Example (3)

- On a kernel compiled with **CONFIG_DEBUG_MUTEXES**



Spin Lock vs Mutex Usage

- Low overhead locking needed? use **spin lock**
- Short lock hold time? use **spin lock**
- Long lock hold time? use **mutex**
- Need to lock in interrupt context? use **spin lock**
- Need to sleep while holding? use **mutex**

Outline

- Introduction
- Atomic Operations
- Spin Locks
- Semaphores and Mutexes
- Other Synchronization Mechanisms
- Ordering and Memory Barriers

Completion Variables

- **Completion variables** are used when a thread needs to signal another one of some event.
  - Waiting thread **sleeps**
- API in include/linux/completion.h
- Declaration / initialization:

```
DECLARE_COMPLETION(comp1); /* static */
struct completion *comp2 = kmalloc(sizeof(struct completion), GFP_KERNEL); /* dynamic */
if (!comp2)
	return -1;
init_completion(comp2);
```

- Thread A:

```
/* signal event: */
complete(comp1);
```

Thread B:

```
/* wait for signal: */
wait_for_completion(comp1);
```

Completion Variables: Usage Example

```
#include <linux/module.h>
#include <linux/kernel.h>
#include <linux/init.h>
#include <linux/slab.h>
#include <linux/delay.h>
#include <linux/kthread.h>
#include <linux/sched.h>
#include <linux/completion.h>

#define PRINT_PREF "[SYNC_COMP] "

unsigned int counter; /* shared data: */
struct completion *comp;
struct task_struct *read_thread, *write_thread;

static int writer_function(void *data)
{
        while (counter != 1234)
                counter++;
        complete(comp);

        do_exit(0);
}
```

```
static int read_function(void *data)
{
        wait_for_completion(comp);
        printk(PRINT_PREF "counter: %d¥n", counter);

        do_exit(0);
}

static int __init my_mod_init(void)
 {
        printk(PRINT_PREF "Entering module.¥n");
        counter = 0;

        comp = kmalloc(sizeof(struct completion), GFP_KERNEL);
        if (!comp) return -1;

        init_completion(comp);
        read_thread = kthread_run(read_function, NULL, "read-thread");
        write_thread = kthread_run(writer_function, NULL, "write-thread");

        return 0;
}
static void __exit my_mod_exit(void)
{
        kfree(comp);
        printk(KERN_INFO "Exiting module.¥n");
}

module_init(my_mod_init);
module_exit(my_mod_exit);
MODULE_LICENSE("GPL");
```

Preemption Disabling

- When a spin lock is held and preemption is disabled:
  - Some situations require preemption disabling without involving spin locks.
  - Example: manipulating per-processor data:

task A manipulates per-processor data foo (not protected by a lock) task A is preempted and task B is scheduled (on the same CPU) task B manipulates variable foo task B completes and task A is rescheduled task A continues manipulating variable foo

  - Might lead to inconsistent state for foo
- API to **disable kernel preemption**
  - can nest and be implemented through a counter
  - preempt_disable()
    - Disable kernel preemption, increment preemption counter
  - preempt_enable()
    - Decrement counter and enable preemption if it reaches 0

Preemption Disabling (2)

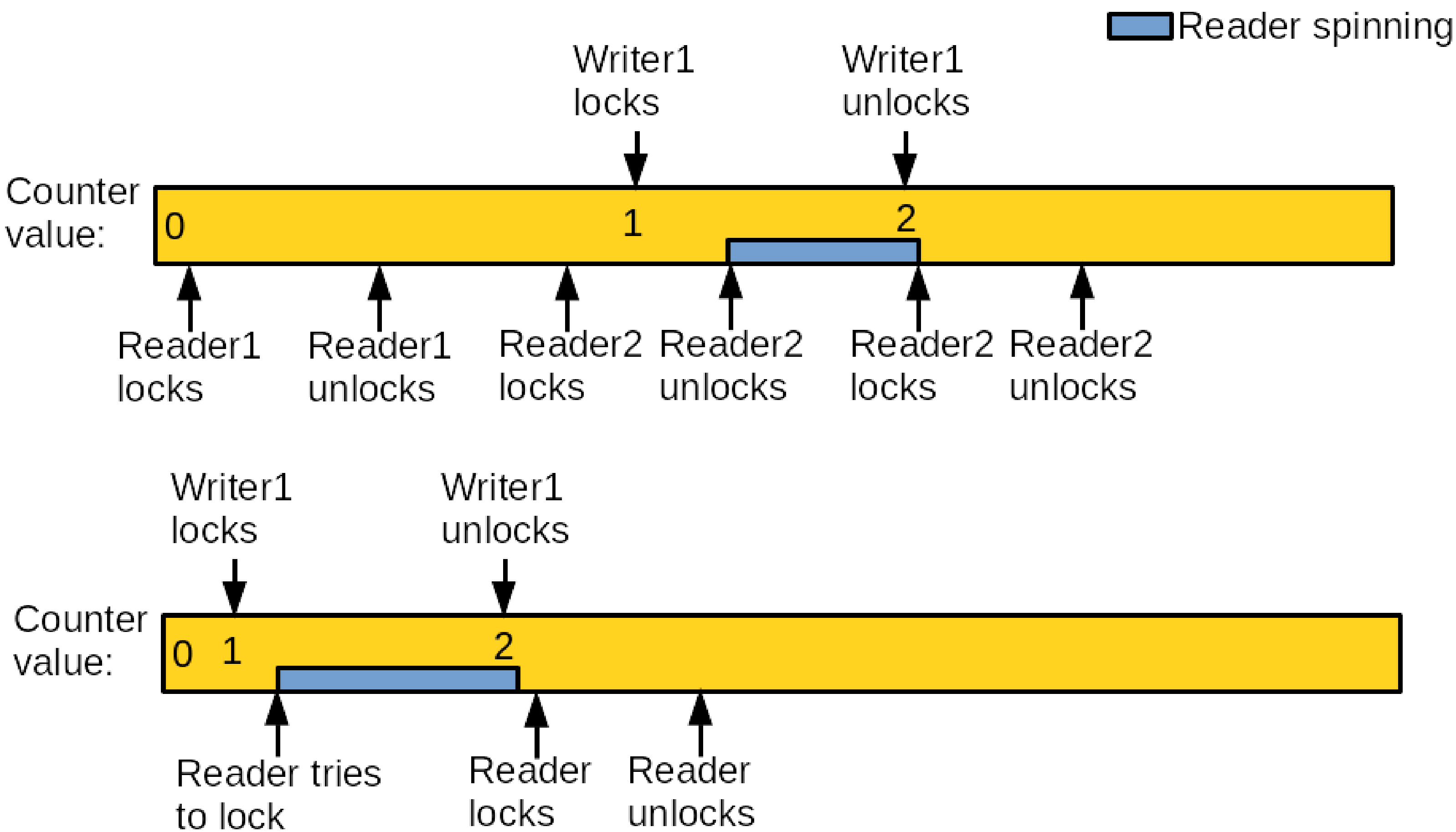
- preempt_enable_no_resched()
  - enables kernel preemption
  - does not check for any pending reschedule
- preempt_count()
  - returns preemption counter
- get_cpu()
  - disables preemption and return the current CPU id

```
int cpu = get_cpu(); /* disable preemption and return current CPU id */

struct *my_struct my_variable = per_cpu_structs_array[cpu];
/* manipulate my_variable */
put_cpu(); /* re-enable preemption */
```

Sequential Locks

- **Sequential lock** / seq lock
  - Reader-writer spinlock **scaling to many readers and favoring writers**
- Implemented with a counter (sequence number)
  - Initialized to 0
  - Incremented by 1 each time a writer takes and releases the lock
- Before and after reading the data, the counter is checked
  - If different, a write operation happened and the read operation must be repeated
  - Prior to the read operation, if the counter is odd, a write is underway.
- API in include/linux/seqlock.h

Sequential Locks (2)



Sequential Locks (3)

- Usage

```
seqlock_t my_seq_lock = DEFINE_SEQLOCK(my_seq_lock);
```

- Write path:

```
write_seqlock(&my_seq_lock);
/* critical (write) region */
write_sequnlock(&my_seq_lock);
```

Read path:

```
unsigned long seq;
do {
        seq = read_seqbegin(&my_seq_lock);
        /* read data here ... */
} while (read_seqretry(&my_seq_lock, seq));
```

- Seq locks are useful when:
  - There are many readers and few writers.
  - Writers should be favored over readers.
- Example: jiffies

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Context

- **Memory reads (load) and write (store) operations can be reordered.**
  - By the compiler (compile time)
  - By the CPU (run time)
- Could be reordered:

```
a = 4;
b = 5;
```

Not reordered:

```
a = 4;
b = a; /* dependency b <- a */
```

- CPU/compiler are not aware about code in other context
  - Communication with hardware
  - Symmetric multiprocessing
- **Memory barriers instruction** allows to force the actual execution of load and stores at some point in the program.

Usage

- rmb() (read memory barrier):
  - No load prior to the code will be reordered after the call
  - No load after the call will be reordered before the call
  - i.e. **commit all pending loads before continuing**
- wmb() (write memory barrier):
  - Same as rmb() with stores instead of loads
- mb():
  - Concerns loads and stores
- barrier():
  - Same as mb() but only for the compiler
- read_barrier_depends()
  - Prevent data-dependent loads (b = a) to be reordered across the barrier
    - Less costly than rmb() as we block only on a subset of pending loads

Usage: Example

- Initially a = 1, b = 2

Thread 1
```
a = 3;
b = 4;
```

Thread 2
```
if (b == 4)
  assert(a == 3);
```

- Cannot assume a == 3 in this example

Usage: Example (2)

- **Correct version:**
- Initially a = 1, b = 2

Thread 1
a = 3;
mb();
b = 4;

Thread 2
If (b == 4)
assert(a == 3);

- **Concrete example of barrier usage:**
  - Thread 1 initializes a data structure
  - Thread 1 spawns thread 2
  - Thread 2 accesses the data structure
- Intuitively, no synchronization is needed, but a wmb() is needed after the data structure initialization.

Usage: SMP Optimizations

- **SMP optimizations:**
  - smp_rmb():
    - rmb() on SMP and barrier() on UP
  - smp_read_barrier_depends():
    - read_barrier_depends() on SMP and barrier() on UP
  - smp_wmb():
    - wmb() on SMP and barrier() on UP
  - smp_mb():
    - mb() on SMP and barrier() on UP
- More info on barriers:
  - Documentation/memory-barriers.txt

Bibliography I

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