W4118 Operating Systems

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Learning goals of this lecture

- Different flavors of synchronization primitives and when to use them, in the context of Linux kernel
- How synchronization primitives are implemented for real
- "Portable" tricks: useful in other context as well (when you write a high performance server)
  - Optimize for common case

Synchronization is complex and subtle

- Already learned this from the code examples we've seen

- Kernel synchronization is even more complex and subtle
  - Higher requirements: performance, protection …
  - Code heavily optimized, "fast path" often in assembly, fit within one cache line

Recall: Layered approach to synchronization

- Hardware provides simple low-level atomic operations, upon which we can build high-level, synchronization primitives, upon which we can implement critical sections and build correct multi-threaded/multi-process programs

Properly synchronized application
High-level synchronization primitives
Hardware-provided low-level atomic operations

Outline

- Low-level synchronization primitives in Linux
  - Memory barrier
  - Atomic operations
  - Synchronize with interrupts
  - Spin locks
- High-level synchronization primitives in Linux
  - Completion
  - Semaphore
  - Futex
  - Mutex

Architectural dependency

- Implementation of synchronization primitives: highly architecture dependent
- Hardware provides atomic operations
- Most hardware platforms provide test-and-set or similar: examine and modify a memory location atomically
- Some don't, but would inform if operation attempted was atomic

Memory barrier motivation

- Evil compiler!
  - Reorder code as long as it correctly maintains data flow dependencies within a function and with called functions

- Evil hardware!
  - Reorder instruction execution as long as it correctly maintains register flow dependencies
  - Reorder memory modification as long as it correctly maintains data flow dependencies

Memory barrier definition

- Memory Barriers: instructions to compiler and/or hardware to complete all pending accesses before issuing any more
  - Prevent compiler/hardware reordering

- Read memory barriers: prevent reordering of read instructions

- Write memory barriers: prevent reordering of write instructions

Linux barrier operations

- barrier – prevent only compiler reordering
- mb – prevents load and store reordering
- rmb – prevents load reordering
- wmb – prevents store reordering

- smp_mb – prevent load and store reordering only in SMP kernel
- smp_rmb – prevent load reordering only in SMP kernels
- smp_wmb – prevent store reordering only in SMP kernels
- set_mb – performs assignment and prevents load and store reordering

- include/asm-i386/system.h

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Atomic operations

- Some instructions not atomic in hardware (smp)
  - Read-modify-write instructions that touch memory twice, e.g., inc, xchg

- Most hardware provides a way to make these instructions atomic
  - Intel lock prefix: appears to lock the memory bus
  - Execute at memory speed

Linux atomic operations

- ATOMIC_INIT – initialize an *atomic_t* variable
- atomic_read – examine value atomically
- atomic_set – change value atomically
- atomic_inc – increment value atomically
- atomic_dec – decrement value atomically
- atomic_add - add to value atomically
- atomic_sub – subtract from value atomically
- atomic_inc_and_test – increment value and test for zero
- atomic_dec_and_test – decrement from value and test for zero
- atomic_sub_and_test – subtract from value and test for zero
- atomic_set_mask – mask bits atomically
- atomic_clear_mask – clear bits atomically

- include/asm-i386/atomic.h

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Linux interrupt operations

- local_irq_disable - disables interrupts on the current CPU
- local_irq_enable - enable interrupts on the current CPU
- local_save_flags - return the interrupt state of the processor
- local_restore_flags - restore the interrupt state of the processor

- Dealing with the full interrupt state of the system is officially discouraged. Locks should be used

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Linux spin lock operations

- spin_lock_init – initialize a spin lock before using it for the first time
- spin_lock – acquire a spin lock, spin waiting if it is not available
- spin_unlock – release a spin lock
- spin_unlock_wait – spin waiting for spin lock to become available, but don't acquire it
- spin_trylock – acquire a spin lock if it is currently free, otherwise return error
- spin_is_locked – return spin lock state

- include/asm-i386/spinlock.h and kernel/spinlock.c

Spin lock usage rules

- Spin locks should not be held for long periods because waiting tasks on other CPUs are spinning, and thus wasting CPU execution time

- Remember, don't call blocking operations (any function that may call schedule()) when holding a spin lock

Linux spin lock implementation

```
__raw_spin_lock_string

1: lock; decb %0  # atomically decrement
   jns   3f       # if clear sign bit (>=0) jump forward to 3
2: rep; nop       # wait
   cmpb $0, %0    # spin – compare to 0
   jle 2b         # go back to 2 if <= 0 (locked)
   jmp 1b         # unlocked; go back to 1 to try again
3:                # we have acquired the lock …
```

spin_unlock merely writes 1 into the lock field.

Variant of spin locks and operations

- Spin locks that serialize with interrupts
- Read-write spin locks (*rwlock_t*)
- Read-write spin locks that serialize with interrupts
- Big reader lock (*brlock*)
- Sequential lock (*seqlock*)

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Completions

- Simple way to ensure execution order: wait and wake-up semantics
- wait_for_complete(*struct completion**) – wait for another thread to call complete()
- compute(*struct completion**) – wake up threads waiting inside wait_for_complete()
- Implemented using spinlock and wait_queue
- include/linux/completion.h and kernel/sched.c

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Linux semaphore operations

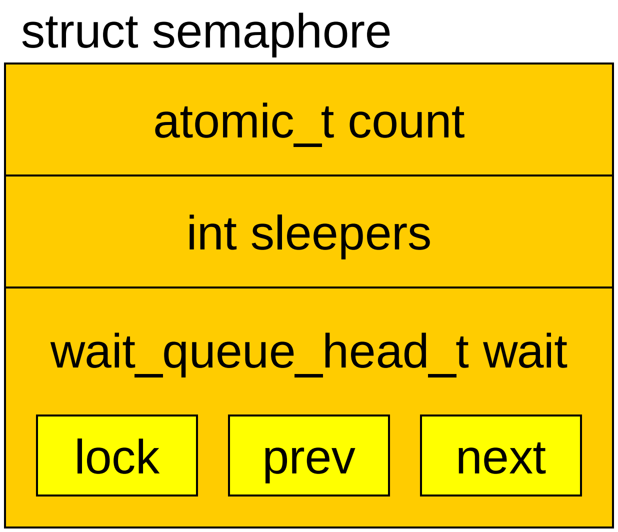
- up – release the semaphore
- down – get the semaphore (can block)
- down_interruptible – get the semaphore, can be woken up if interrupt arrives
- down_trylock – try to get the semaphore without blocking, otherwise return an error
- include/asm-i386/semaphore.h and arch/i386/kernel/semaphore.c

Linux semaphore implementation

- Goal: optimize for uncontended (common) case
- Implementation idea
  - Uncontended case: use atomic operations
  - Contended case: use spin locks and wait queues

Linux semaphore structure

- Struct semaphore
  - count (atomic_t):
    - > 0: free;
    - = 0: in use, no waiters;
    - < 0: in use, waiters
  - sleepers:
    - 0 (none)
    - 1 (some), occasionally 2
  - wait: wait queue
- implementation requires lower-level synchronization primitives
  - atomic updates, spinlock, interrupt disabling



Contrived (buggy) semaphore implementation

```
up (struct semaphore* s)
{
    if(atomic_inc_positive(&s->count))
        return;
    wake_up(&s->wait);
}
```

```
down (struct smaphore *s)
{
    if(!atomic_dec_negative(&s->count))
        return; // uncontended
    // contended
    add_wait_queue_exclusive(&s->wait, self);
}
```

- Common case: only one atomic instruction
- Problem
  - Concurrent calls to up() and down()?
  - Concurrent calls to down()?

The real down()

```
inline down:
   movl $sem, %ecx  # why does this work?
   lock; decl (%ecx)# atomically decr sem count
   jns 1f                 # if not negative jump to 1
   lea %ecx, %eax   # move into eax
   call  __down_failed    #
1:                  # we have the semaphore
```

```
down_failed:
   pushl %edx       # push edx onto stack (C)
   pushl %ecx       # push ecx onto stack
   call  __down           # call C function
   popl %ecx        # pop ecx
   popl %edx        # pop edx
   ret
```

include/asm-i386/semaphore.h and arch/i386/kernel/semaphore.c

__down()

```
tsk->state = TASK_UNINTERRUPTIBLE;
spin_lock_irqsave(&sem->wait.lock, flags);
add_wait_queue_exclusive_locked(&sem->wait, &wait);
sem->sleepers++;
for (;;) {
    int sleepers = sem->sleepers;
    /*
     * Add "everybody else" into it. They aren't playing,
     * because we own the spinlock in the wait_queue head
     */
    if (!atomic_add_negative(sleepers - 1, &sem->count)) {
          sem->sleepers = 0;
          break;
    }
    sem->sleepers = 1;      /* us - see -1 above */
    spin_unlock_irqrestore(&sem->wait.lock, flags);
    schedule();
    spin_lock_irqsave(&sem->wait.lock, flags);
    tsk->state = TASK_UNINTERRUPTIBLE;
}
remove_wait_queue_locked(&sem->wait, &wait);
wake_up_locked(&sem->wait);
spin_unlock_irqrestore(&sem->wait.lock, flags);
tsk->state = TASK_RUNNING;
```

Linux/lib/semaphore-sleepers.c

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Futex motivation

- Synchronization of kernel-level threads: expensive
  - Each synchronization operation traps into kernel
- Futex: optimize for the uncontended (common) case
  - Uncontended → no kernel involvement
  - Contended → trap into kernel

Futex implementation

- Borrows from Linux kernel semaphore implementation
- Data structure
  - An aligned integer in user space
  - A wait queue in kernel space
- Operations
  - Uncontended case: atomic operations, user space
  - Contended case: spin locks and wait queues, kernel space
- pthread mutex, semaphore, and condition variables use futex

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Linux mutexes: motivation

- Introduced in 2.6.16.
- "90% of semaphores in kernel are used as mutexes, 9% of semaphores should be spin_locks." Andrew Morton
- Slow paths are more critical for highly contended semaphores on SMP
- Mutexes are simpler

Linux mutex operations

- mutex_unlock – release the mutex
- mutex_lock – get the mutex (can block)
- mutex_lock_interruptible – get the mutex, but allow interrupts
- mutex_trylock – try to get the mutex without blocking, otherwise return an error
- mutex_is_locked – determine if mutex is locked