Kernel Synchronization

with material from Understanding the Linux Kernel (O'Reilly)

Synchronization In The Kernel

- Past lectures:
  - Synchronization constructs
- Today's lecture:
  - What does this stuff look like in an OS?
  - We have source code for Linux…
  - We mostly run on x86 platforms
  - Lets look at some specifics.

Disabling Interrupts

- Key observations:
  - On a uni-processor, an operation is atomic if no context-switch is allowed in the middle of the operation
  - Context switch occurs because of:
    - Internal events: system calls and exceptions
    - External events: interrupts
  - Mutual exclusion can be achieved by preventing context switch
- Prevention of context switch
  - Eliminate internal events: easy (under program control)
  - Eliminate external events: disable interrupts
    - Hardware delays the processing of interrupts until interrupts are enabled

Lock Implementation: A Naïve Solution

```
Lock::Acquire() { disable interrupts; }
Lock::Release() { enable interrupts;}
```

- Will this work on a uni-processor?
- What is wrong with this solution?
  - Once interrupts are disabled, the thread can't be stopped ➔ Can starve other threads
  - Critical sections can be arbitrarily long ➔ Can't bound the amount of time needed to respond to interrupts
- But this is used all over the place in uniprocessor OSes to do short tasks. It is a large source of bugs. What would typical failure conditions be?

Disabling Interrupts in Linux

- Usually some small number of interrupt levels, statically assigned (e.g., reset = 0, timer = 1, network = 3, disk = 4, software = 7)
  - When you "disable interrupts" you disable them for your level and higher.
  - When you reenable interrupts, you need to do so at the previous level.
  - Where do you store the level in the meantime?
    - A. Local variable
    - B. Global variable
    - C. Hardware register

```
unsigned long flags;
local_irq_save( flags );  // Disable & save
  do_whatever;
local_irq_restore( flags ); // Reenable
```


Using Locks Correctly

- Make sure to release your locks along every possible execution path.

```
unsigned long flags;
local_irq_save( flags );  // Disable & save
  …
  if(somethingBad) {
     local_irq_restore( flags );
     return ERROR_BAD_THING;
  }
  …
local_irq_restore( flags ); // Reenable
return 0;
```

Entering Linux

- An OS is a server that responds to requests, from user code and from devices.
- How to enter the Linux kernel
  - `int 0x80`, which is the system call instruction on the x86 by convention.
  - External device sends a signal to a programmable interrupt controller (PIC) by using an IRQ (interrupt request) line, and that interrupt is enabled.
  - A process in kernel mode causes a page fault.
  - A process in a multi-processor system executing in kernel mode raises an inter-processor interrupt.
- Interrupt, exception, or softirq handling can interrupt a process running in kernel mode, but when the handler terminates, the kernel control path of the process resumes.

Linux Synchronization Primitives

Technique	Description	Scope
Atomic Operation	Atomic read-modify-write instruction	All CPUs
Memory barrier	Avoid instruction re-ordering	Local CPU
Spin lock	Lock with busy wait (readers/writers spin locks)	All CPUs
Semaphore	Lock with blocking wait (R/W semaphores)	All CPUs
Local interrupt disable	Forbid interrupt handling on single CPU	Local CPU
Local softirq disable	Forbid deferrable function handling on a single CPU	Local CPU
Global interrupt disable	Forbid interrupt and softirq handling on all CPUs	All CPUs

Scope of Synch Primitives

- The test&set instruction is local to a single CPU in a multi-CPU system.
  - A. True
  - B. False

Atomic Operations

- Assembly language instructions that make 0 or 1 aligned memory access (a 32-bit aligned access has the last 2 address bits equal to zero).
- Read-modify-write instructions (like inc and dec) with the lock prefix. Locks the memory bus.
- Linux provides wrappers for these operations.
  - atomic_set(v,i) sets *v=i
  - atomic_inc_and_test(v) Add 1 to *v and return 1 if value is now zero, 0 otherwise.

Memory Barriers

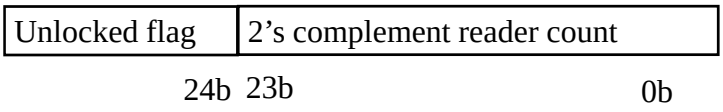
- Compiler reorders your memory accesses.
- Memory barrier says, “wait here until all outstanding memory operations have completed.”
- rmb() expands to
- asm volatile(“lock;addl $0,0(%%esp)”:::”memory”);
  - volatile – disables compiler reorder of instruction
  - memory – forces compiler to assume any RAM can change from this instruction.
  - lock prefix locks memory bus, and requires all previous reads to complete.
- Example use
  - new->next = list_element->next;
  - wmb();
  - list_element->next = new;

Spin Locks

- CPU “spins,” executing instructions waiting for lock to free.
  - Only useful on multi-processors
  - Insures only one kernel thread runs a routine at a time
- Value of 1 means lock is free
-
```
spin_lock(spinlock_t slp) {
1: lock; decb slp
   jns 3f
2: cmpb $0, slp
   pause    // p4-reduces power
   jle 2b   // back compat rep;nop
   jmp 1b
3:
```

R/W Spin Locks – space optimized data structure

- Many locks in kernel, so they should be small.
  - Interpret bit ranges.



- 0x01000000 – Idle, not locked and no readers
- 0x00000000 – Aquired for writing, no readers
- 0x00FFFFFE – Aquired by 2 readers
- read_lock() = lock; subl $1, (rwlp)\n jns 1f
- read_unlock() = lock; incl rwlp
- rw_lock() = lock; subl %0x01000000, (rwlp)\n jz 1f
- rw_unlock() = lock; addl $0x01000000, rwlp

Semaphores

- Kernel semaphores suspend a waiting process, so can't be called from interrupt handlers and deferrable functions.
  - atomic_t count; // 1=available 0=busy -1=one waiting
  - wait_queue; // wait queue list
  - int sleepers; //flag, 1 if sleepers, optimization
- **`down()`** – acquire **`up()`** – release
- **`down_interruptable()`**
  - Used by device drivers. Suspend me, but if I get a signal, take me off the wait queue & return error.
- Read/write semaphores. Allows multiple readers.
  - Queues waiters, so it is fair to writers.
- Semaphore implementation only locks when manipulating the sleep queue.

Linux Use of Semaphores

- Linux uses semaphores in which processing path (primarily)?
  - A. Interrupt Handlers
  - B. System call service routines
  - C. Deferrable kernel functions
  - D. Device drivers
  - E. Kernel threads

Completions
Solving race condition with temporary Semaphores

Thread A, CPU 0

- Alloc semaphore S
- Pass sema to B → Accept sema S
- down(S)

Thread B, CPU 1

- free(S) ← up(S)

- up(S) and free(S) execute concurrently.
  - lock only protects sleep queue, not whole semaphore
- Lock protects entire Completion.
  - Slower, but safer.

Local Interrupt Disable

- local_irq_disable()/local_irq_enable()
  - Disables and reenables interrupts
  - Executes cli/sti on x86
- But interrupts can be nested, so what interrupt level to we return to?
  - unsigned long flags;
  - local_irq_disable(flags);
  - …Read or update a data structure…
  - local_irq_enable(flags);
- Disable clears the IF flag of the eflags register, and saves register in variable. Enable restores previous register value.

Uses of Synchronization in the Kernel

- Short Kernel Critical Sections
  - Disable interrupts (& grab spin lock on MPs)
- Long Critical Sections
  - Separated into “top” and “bottom”
  - top - disable interrupts (& grab spin lock on MPs)
  - bottom – bottom halves don’t interrupt each other, so no sync needed on UP. On MP uses a lock to protect data structures from concurrent access.
- Interrupt Protection levels
  - top-half interrupt handlers
  - bottom-half interrupt handlers
  - kernel-system service routines
  - user-mode programs (preemptible)