Architecture of the Linux kernel
or: The world beyond the syscall barrier

by

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Prerequisites

Due to the technical nature of this presentation, the audience should be familiar with the following subjects

- experience in programming on a Linux/*NIX system
  - C language preferred
- general knowledge about computer hardware
  - interrupts / IO / DMA
- general knowledge about modern CPU architecture
  - address space / MMU
  - "protected mode" / supervisor mode / ...
OS kernel provides
- hardware abstraction (file I/O, network I/O, ...)
- resource allocation / limiting
- address separation
- privilege separation
- IPC

the traditional process model in *NIX operating systems
- processes reside in separate virtual address spaces
- kernel only executes one process (init) at bootup
- all other processes descend from init
- processes are scheduled and preempted by the kernel
- processes invoke system functions via syscalls.
System calls

Definition

- a userspace process enters the kernel
- mechanism is CPU architecture dependent
  - can be software interrupt (int 0x80)
  - can be special asm instruction (sysenter)
- arguments are passed on the stack
- common examples
  - open/close/read/write
  - exit/fork/execve/kill
  - syscall, implements (socket/bind/connect/listen)
- about 270 system calls in 2.6.x kernels
Invocation of system call

chronological order of events in case of a system call

- **userspace process calls library function**
  - library function is executed within the process’ address space
  - library will eventually issue a syscall, pushing arguments on the stack
  - library will issue syscall (int 0x80 / sysenter / ...)

- **execution will switch to syscall context in kernel mode**
  - kernel will look up syscall table and dispatch to respective function
  - syscall function in the kernel will handle the syscall
  - all data between kernel/userspace needs to be copied between address spaces
apart from scheduling between different userspace processes, the kernel has different jobs like reacting to an external event

- **hardirq**
  - hardware interrupt line was triggered
- **softirq**
  - the workhorse behind a hardirq
- **userspace**
  - executing within userspace process
- **syscall**
  - invoked by a system call from userspace
- **vsyscall**
  - virtual system calls, executed in userspace context
hardirq context

- interrupt generated by hardware is received + handled
- can be interrupted by other hardirq’s
- does only minimal job and returns
- examples
  - packet has arrived on network board
  - character was received on serial port
  - dma read/write to disk drive has completed
  - timer interrupt went off

- in most cases, a hardirq is followed by softirq or tasklet.
softirq context

- softirqs are run after hardirq
- do the real work associated with a hardirq
- multithreaded (can run simultaneously on multiple cpus)
- examples
  - network receive softirq
  - timer softirq

- prior to softirq's, Linux had so-called 'bottom halves'
  - softirq introduced in 2.4.x (net rx/tx softirq)
  - bottom halves removed in 2.6.x
  - difference: only one BH can be run at a time
  - BH’s have to be converted to tasklets in 2.6.x
Tasklets are somewhat in between of softirq’s and bottom halves

- One particular tasklet cannot run on multiple CPUs simultaneously
- Different tasklets can run on different CPUs simultaneously

Otherwise, same as softirq context

- Tasklets are impl. inside the ’tasklet softirq’
syscall / userspace context

- **userspace context**
  - in userspace, executing a process

- **syscall context**
  - inside kernel, when userspace process issues syscall()

- **vsyscalls (virtual syscalls)**
  - first introduced with the x86-64 (AMD Opteron) arch
  - fast read-only access to kernel data structures
  - can do stuff like gettimeofday() without context switch
Due to reentrancy and SMP, synchronization issues arise:

- **simple case: UP system**
  - softirq can be interrupted by hardirq
    - thus, shared structures (queues, ...) need to be protected
- **complex case: SMP system**
  - softirq can run at the same time on multiple CPU’s
  - as softirqs are multithreaded, synchronization between threads has to be implemented
synchronization primitives

busy-waiting locks

- **spinlocks**
  - if lock was not taken, take it and continue
  - if lock was taken, bysy-loop until it is free

- **rwlocks**
  - special case of spinlocks
  - useful when structure protected by lock is often read but rarely updated/written to
  - allows either
    - multiple readers simultaneously, or
    - only one writer [and no readers]

- **brlocks**
  - super-fast read/write locks, with write-side penalty
  - avoid cache ping-pong in multi reader case
  - only in kernel 2.4.x
sleeper locks

- semaphores
  - if semaphore can be acquired, continue
  - if semaphore cannot be acquired, put current process to sleep
    - once semaphore is available again, wakeup process
  - WARNING: can only be used for sync userspace/syscall context
new locking primitives in 2.6.x

- seqlocks
  - introduced with vsyscalls in 2.5/2.6
  - reader/writer consistent mechanism without starving writers
  - readers never block but may have to retry if write in progress

- read copy update
  - new lockless mechanism in kernel 2.5/2.6
  - defers update of data structure until all CPU’s have scheduled and thus nobody has any references left
example: incoming network packet

hardirq context
- NIC issues interrupt line after a packet was received
- kernel enters (arch/i386/kernel/entry.S:common_interrupt)
- core interrupt handler (arch/i386/kernel/irq.c:do_IRQ)
- hardirq handler of network driver
  (drivers/net/tulip/interrupt.c:tulip_interrupt)
- net/core/dev.c:netif_rx(): append skb to backlog queue
example: incoming network packet

softirq context

- net/core/dev.c:net_rx_action()
- net/core/dev.c:process_backlog()
- net/core/dev.c:netif_receive_skb()
- net/core/dev.c:deliver_skb()
- net/ipv4/ip_input.c:ip_rcv()
  - netfilter prerouting hook
- net/ipv4/ip_input.c:ip_rcv_finish()
  - call routing code
- net/ipv4/ip_input.c:ip_local_deliver()
  - netfilter localin hook
- net/ipv4/ip_input.c:ip_local_deliver_finish()
  - call l4 protocol
- net/ipv4/udp.c:udp_rcv()
  - lookup socket, if any
- include/net/sock.h:sock_queue_rcv_skb()
  - enqueue into socket receiver queue
- net/core/sock.c:sock_def_readable()
  - wake_up_interruptible() on socket waitqueue
- return from recv() via socketcall
example: reading of a file
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