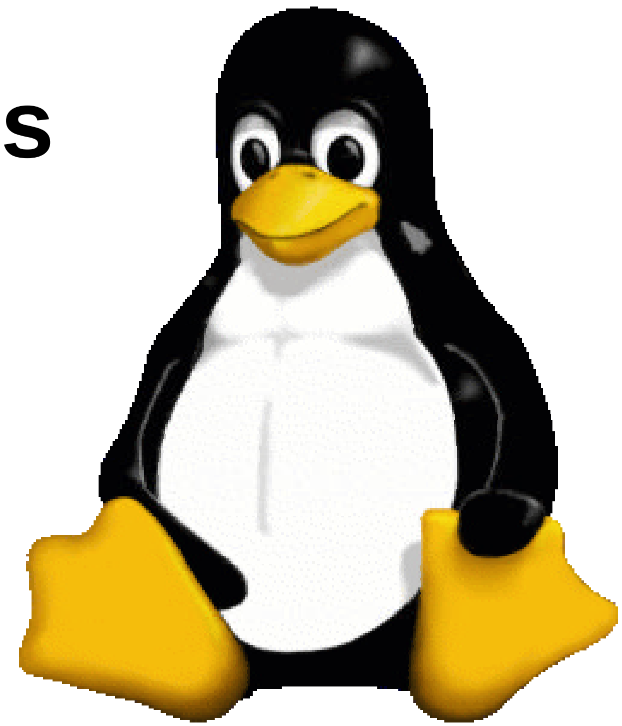
The Linux Kernel: Signals & Interrupts



Signals

- Introduced in UNIX systems to simplify IPC.
- Used by the kernel to notify processes of system events.
- A signal is a short message sent to a process, or group of processes, containing the number identifying the signal.
  - No data is delivered with traditional signals.
  - POSIX.4 defines i/f for queueing & ordering RT signals w/ arguments.

Example Signals

- Linux supports 31 non-real-time signals.
- POSIX standard defines a range of values for RT signals:
  - **`SIGRTMIN 32 … SIGRTMAX (_NSIG-1)`** in **`<asm-*/signal.h>`**

#	Signal Name	Default Action	Comment
1	SIGHUP	Abort	Hangup terminal or process
2	SIGINT	Abort	Keyboard interrupt (usually Ctrl-C)
…			
9	SIGKILL	Abort	Forced process termination
10	SIGUSR1	Abort	Process specific
11	SIGSEGV	Dump	Invalid memory reference
…			

Signal Transmission

- Signal sending:
  - Kernel updates descriptor of destination process.
- Signal receiving:
  - Kernel forces target process to “handle” signal.
- *Pending signals* are sent but not yet received.
  - Up to one pending signal per type for each process, except for POSIX.4 signals.
  - Subsequent signals are discarded.
  - Signals can be blocked, i.e., prevented from being received.

Signal-Related Data Structures

- **sigset_t** stores array of signals sent to a process.
- The process descriptor (**struct task_struct** in **<linux/sched.h>**) has several fields for tracking sent, blocked and pending signals.

```
struct sigaction {
    void (*sa_handler)();/* handler address, or
                            SIG_IGN, or SIG_DFL */
    sigset_t sa_mask;    /* blocked signal list */
    int sa_flags;     /* options e.g., SA_RESTART */
}
```

Sending Signals

- A signal is sent due to occurrence of corresponding event (see **`kernel/signal.c)`**.
- e.g., **`send_sig_info(int sig, struct siginfo *info, struct task_struct *t);`**
  - **`sig`** is signal number.
  - **`info`** is either:
    - address of RT signal structure.
    - 0, if user mode process is signal sender.
    - 1, if kernel is signal sender.
- e.g., **`kill_proc_info(int sig, struct siginfo *info, pid_t pid);`**

Receiving Signals

- Before process ***p*** resumes execution in user mode, kernel checks for pending non-blocked signals for ***p***.
  - Done in **`entry.S`** by call to **`ret_from_intr()`**, which is invoked after handling an interrupt or exception.
  - **`do_signal()`** repeatedly invokes **`dequeue_signal()`** until no more non-blocked pending signals are left.
  - If the signal is not ignored, or the default action is not performed, the signal must be *caught*.

Catching Signals

- **`handle_signal()`** is invoked by **`do_signal()`** to execute the process's registered signal handler.
- Signal handlers reside (& run) in user mode code segments.
  - **`handle_signal()`** runs in kernel mode.
  - Process first executes signal handler in user mode before resuming "normal" execution.
- Note: Signal handlers can issue system calls.
  - Makes signal mechanism complicated.
  - Where do we stack state info while crossing kernel-user boundary?

Re-execution of System Calls

- "Slow" syscalls e.g. blocking read/write, put processes into waiting state:
  - **TASK_(UN)INTERRUPTIBLE**.
  - A task in state **TASK_INTERRUPTIBLE** will be changed to the **TASK_RUNNING** state by a signal.
  - **TASK_RUNNING** means a process can be scheduled.
    - If executed, its signal handler will be run *before completion* of "slow" syscall.
    - The syscall does not complete by default.
    - If **SA_RESTART** flag set, syscall is restarted after signal handler finishes.

Real-Time Signals

- Real-Time signals are *queued* as a list of **`signal_queue`** elements:

```
struct signal_queue {
    struct signal_queue *next;
    siginfo_t info; /* See asm-*/siginfo.h */
}
```

- A process's descriptor has a **`sigqueue`** field that points to the first member of the RT signal queue.
- **`send_sig_info()`** enqueues RT signals in a signal_queue.
- **`dequeue_signal()`** removes the RT signal.

RT Signal Parameters

- **siginfo_t** contains a member for RT signals.
- The argument to RT signals is a **sigval_t** type:

```
typedef union sigval {
    int sigval_int;
    void *sival_ptr;
} sigval_t;
```

- Extensions?
  - Explicit scheduling of signals and corresponding processes.

Signal Handling System Calls

- **`int sigaction(int sig, const struct sigaction *act, struct sigaction *oact);`**
  - Replaces the old **`signal()`** function.
  - Used to bind a handler to a signal.
  - For RT signals, the handler's prototype is of form:
    - **`void (*sa_sigaction)(int, siginfo_t *, void *);`**
- See Steven's "Advanced Programming in the UNIX Environment" for more…

Interrupts

- Interrupts are events that alter sequence of instructions executed by a processor.
- *Maskable interrupts*:
  - Sent to **`INTR`** pin of x86 processor. Disabled by clearing **`IF`** flag of eflags register.
- *Non-maskable interrupts*:
  - Sent to **`NMI`** pin of x86 processor. Not disabled by clearing **`IF`** flag.
- *Exceptions*:
  - Can be caused by faults, traps, programmed exceptions (e.g., syscalls) & hardware failures.

Interrupt & Exception Vectors

- 256 8-bit vectors on x86 (0..255):
  - Identify each interrupt or exception.
- Vectors:
  - 0..31 for exceptions & non-maskable interrupts.
  - 32..47 for interrupts caused by IRQs.
  - 48..255 for “software interrupts”.
    - Linux uses vector 128 (0x80) for system calls.

IRQs & Interrupts

- Hardware device controllers that issue interrupt requests, do so on an IRQ (Interrupt ReQuest) line.
- IRQ lines connect to input pins of *interrupt controller* (e.g., 8259A PIC).
- Interrupt controller repeatedly:
  - Monitors IRQ lines for raised signals.
    - Converts signal to vector & stores it in an I/O port for CPU to access via data bus.
    - Sends signal to INTR pin of CPU.
    - Clears INTR line upon receipt of ack from CPU on designated I/O port.

Example Exceptions

#	*Exception*	*Exception Handler*	*Signal*
0	Divide Error	divide_error()	SIGFPE
1	Debug	debug()	SIGTRAP
…			
6	Invalid Opcode	invalip_op()	SIGILL
…			
14	Page Fault	page_fault()	SIGSEGV
…			

Interrupt Descriptor Table

- A system *Interrupt Descriptor Table* (IDT) maps each vector to an interrupt or exception handler.
  - IDT has up to 256 8-byte *descriptor entries*.
  - **`idtr`** register on x86 holds base address of IDT.
- Linux uses two types of descriptors:
  - *Interrupt gates* & *trap gates*.
    - Gate descriptors identify address of interrupt / exception handlers
    - Interrupt gates clear **`IF`** flag, trap gates don't.

Interrupt Handling

- CPU checks for interrupts after executing each instruction.
- If interrupt occurred, control unit:
  - Determines vector ***i***, corresponding to interrupt.
  - Reads ***ith*** entry of IDT referenced by **`idtr`**.
    - IDT entry contains a *segment selector*, identifying a *segment descriptor* in the *global descriptor table* (GDT), that identifies a memory segment holding handler fn.
  - Checks interrupt was issued by authorized source.

Interrupt Handling …continued…

- Control Unit then:
  - Checks for a change in privilege level.
    - If necessary, switches to new stack by:
      - Loading **`ss`** & **`esp`** regs with values found in the *task state segment* (TSS) of current process.
      - Saving old **`ss`** & **`esp`** values.
  - Saves state on stack including **`eflags`**, **`cs`** & **`eip`**.
  - Loads **`cs`** & **`eip`** w/ segment selector & offset fields of gate descriptor in ***ith*** entry of IDT.
- Interrupt handler is then executed!

Protection Issues

- A *general protection exception* occurs if:
  - Interrupt handler has lower privilege level than a program causing interrupt.
  - Applications attempt to access interrupt or trap gates.
  - ***What would it take to vector interrupts to user level?***
- Programs execute with a current privilege level (CPL).
- e.g., If gate descriptor privilege level (DPL) is lower than CPL, a general protection fault occurs.

Gates, Gates but NOT *Bill Gates*!

- Linux uses the following gate descriptors:
  - ***Interrupt gate***:
    - DPL=0, so cannot be accessed by user mode progs.
  - ***System gate***:
    - DPL=3, so can be accessed by user mode progs.
    - e.g., vector 128 accessed via syscall triggered by int 0x80.
  - ***Trap gate***:
    - DPL=0. Trap gates are used for activating exception handlers.

Initializing IDT

- Linux uses the following functions:
  - **`set_intr_gate(n, addr);`**
  - **`set_trap_gate(n,addr);`**
  - **`set_system_gate(n,addr);`**
    - Insert gate descriptor into ***nth*** entry of IDT.
    - **`addr`** identifies offset in kernel's code segment, which is base address of interrupt handler.
    - DPL value depends on which fn (above) is called.
  - e.g., **`set_system_gate(0x80,&system_call);`**