Linux Kernel Programming
Interrupts and Interrupt Handlers

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Outline

1. Interrupts: general information
2. Registering & writing an interrupt handler
3. Interrupt context
4. Interrupt handling internals in Linux
5. /proc/interrupts
6. Interrupt control

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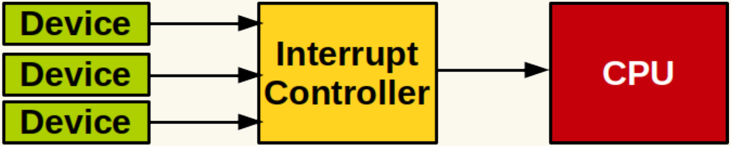
Interrupts: general information

Interrupts

- Compared the the CPU, devices are **slow**
  - Ex: when a read request is issued to the disk, it is sub-optimal to wait, doing nothing until the data is ready (in RAM)
    - Need to know when the hardware is ready
- *Polling* can create a lot of overhead
  - Having the CPU check regularly the status of the hardware
- **The solution is to have *hardware devices signal the CPU* that they need attention**
  - **Interrupts**
    - A key has been pressed on the keyboard
    - A packet has been received on the network card
    - etc.

Interrupts: general information

Interrupts (2)



- Interrupts are electrical signals multiplexed by the interrupt controller
  - Sent on a specific pin of the CPU
- Once an interrupt is received, a dedicated function is executed:
  - ***Interrupt handler***
- They can be received in a completely non-deterministic way:
  - **The kernel/user space can be interrupted at (nearly) any time to process an interrupt**

Interrupts: general information

Interrupts (3)

- Device identifier: **interrupt line** or **Interrupt ReQuest (IRQ)**
- Function executed by the CPU: **interrupt handler** or **Interrupt Service Routine (ISR)**

- 8259A interrupt lines:
  - IRQ #0: system timer
  - IRQ #1: keyboard controller
  - IRQ #3 and #4: serial port
  - IRQ #5: terminal
  - IRQ #6: floppy controller
  - IRQ #8: RTC
  - IRQ #12: mouse
  - IRQ #14: ATA (disk)
- Source [2]

- *Some interrupt lines can be shared among several devices*
  - True for most modern devices (PCIe)

Interrupts: general information

Exceptions

- **Exception** are interrupt issued by the CPU executing some code
  - ***Software*** interrupts, as opposed to ***hardware*** ones (devices)
  - Happen synchronously with respect to the CPU clock
  - Examples:
    - **Program faults**: divide-by-zero, page fault, general protection fault, etc.
    - **Voluntary exceptions**: `INT` assembly instruction, for example for syscall invocation
    - List: [1]
- Exceptions are managed by the kernel the same way as hardware interrupts

Interrupts: general information

Interrupt handlers

- The **interrupt handlers** (ISR) are kernel C functions associated to interrupt lines
  - Specific prototype
  - Run in **interrupt context**
    - Opposite to process context (system call)
    - Also called atomic context as ***one cannot sleep in an ISR***: it is not a schedulable entity
- Managing an interrupt involves two high-level steps:
  1. **Acknowledging the reception** (mandatory, fast)
  2. Potentially **performing additional work** (possibly slow)
     - Ex: processing a network packet available from the Network Interface Card (NIC)

Interrupts: general information

Top-halves vs bottom-halves

- ***Interrupt processing must be fast***
  - We are indeed interrupting user processes executing (user/kernel space)
  - In addition, other interrupts may need to be disabled during an interrupt processing
- ***However, it sometimes involves performing significant amount of work***
- **Conflicting goals**
  - Thus, processing an interrupt is broken down between:
    1. **Top-half**: time-critical operations (ex: ack), run immediately upon reception
    2. **Bottom-half**: less critical/time-consuming work, run later with other interrupts enabled

Interrupts: general information

Top-half & bottom-half example

- drivers/input/keyboard/omap-keypad.c

```c
/* (block 1) */
static int omap_kp_probe(struct
      platform_device *pdev)
{
  /* ... */
  omap_kp->irq = platform_get_irq(pdev, 0);
  if(omap_kp->irq >= 0) {
    if(request_irq(omap_kp->irq,
      omap_kp_interrupt, 0,
        "omap-keypad", omap_kp) < 0)
      goto err4;
  }
}
```

```c
/* (block 3) */
static DECLARE_TASKLET_DISABLED(
  kp_tasklet, omap_kp_tasklet, 0);
```

```c
/* (block 2) */
/* Top half: interrupt handler (ISR) */
static irqreturn_t omap_kp_interrupt(int
      irq, void *dev_id)
{
  /* disable keyboard interrupt */
  omap_writew(1, /* ... */);

  tasklet_schedule(&kp_tasklet);
  return IRQ_HANDLED;
}
```

```c
/* (block 4) */
/* Bottom half */
static void omap_kp_tasklet(unsigned long
      data)
{
  /* performs lot of work */
}
```

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Registering & writing an interrupt handler

Interrupt handler registration: `request_irq()`

- **`request_irq()`** (in `includes/linux/interrupt.h`)

```c
static inline int __must_check
request_irq(unsigned int irq, irq_handler_t handler, unsigned long flags,
  const char *name, void *dev)
```

- `irq`: interrupt number
- `handler`: function pointer to the actual handler
  - prototype:

```c
typedef irqreturn_t (*func)(int irq, void *data);
```

- `name`: String describing the associated device
  - For example used in `/proc/interrupts`
- `dev`: unique value identifying a device among a set of devices sharing an interrupt line

Registering & writing an interrupt handler

Interrupt handler registration: registration flags

Registration flags:

- `IRQF_DISABLED`: **disables all interrupts when processing this handler**
  - Bad form, reserved for performance sensitive devices
  - Generally handlers run with all interrupts enabled except their own
  - **Removed in 4.1**
- `IRQF_SAMPLE_RANDOM`: this interrupt frequency will **contribute to the kernel entropy pool**
  - For Random Number Generation
  - **Do not set this on periodic interrupts!** (ex: timer)
    - RNG is used for example for cryptographic key generation
- `IRQF_TIMER`: system **timer**
- `IRQF_SHARED`: interrupt line can be **shared**
  - Each of the handlers sharing the line must set this

Registering & writing an interrupt handler

Interrupt handler registration: `irq_request()` (2)

- `irq_request()` returns 0 on success, or standard error code
  - `-EBUSY`: interrupt line already in use
- `irq_request()` **can sleep**
  - Creating an entry in the `/proc` virtual filesystem
    - `kmalloc()` in the call stack

Registering & writing an interrupt handler

An interrupt example, freeing an interrupt handler

- `omap-keypad` registration and handler:

```
static int omap_kp_probe(struct
      platform_device *pdev)
{
  /* ... */
  if(request_irq(omap_kp->irq,
      omap_kp_interrupt, 0, "omap-keypad",
       omap_kp) < 0)
    goto err4;
}
```

```
static irqreturn_t omap_kp_interrupt(int
      irq, void *dev_id)
{
  omap_writew(1, OMAP1_MPUIO_BASE +
      OMAP_MPUIO_KBD_MASKIT);
  tasklet_schedule(&kp_tasklet);
  return IRQ_HANDLED;
}
```

- Freeing an irq is made through `free_irq()`:

```
void free_irq(unsigned int irq, void
      *dev);
```

- `omap-keypad` example:

```
static int omap_kp_remove(struct
      platform_device *pdev)
{
  /* ... */
  free_irq(omap_kp->irq, omap_kp);
  /* ... */
  return 0;
}
```

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Registering & writing an interrupt handler

Inside the interrupt handler

- **Interrupt handler prototype:**

```c
static irqreturn_t handler_name(int irq, void *dev);
```

- **`dev` parameter:**
  - Must be unique between handlers sharing an interrupt line
  - Set when registering the handler and can be accessed by the handler
    - ex: pass a pointer to a data structure representing the device
- **Return value:**
  - `IRQ_NONE`: the expected device was not the source of the interrupt
  - `IRQ_HANDLED`: correct invocation
  - This macro can be used: `IRQ_RETVAL(x)`
    - If `(x != 0)`, expands into `IRQ_HANDLED`, otherwise expands into `IRQ_NONE` (example: `vsc_stat_interrupt` in `drivers/ata/sata_vsc.c`)
- Interrupt handlers do not need to be **reentrant** (thread-safe)
  - The corresponding interrupt is disabled on all cores while its handler is executing

Registering & writing an interrupt handler

Shared handlers

- **Shared handlers**
  - On registration:
    - `IRQ_SHARED` flag
    - `dev` must be unique (ex: a pointer to a data structure representing the device in question)
  - **Handler must be able to detect that the device actually generated the interrupt it is called from**
    - When an interrupt occurs on a shared line, *the kernel executes sequentially all the handlers sharing this line*
    - Need hardware support at the device level and detection code in the handler

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Interrupt context

- The kernel can execute in **Interrupt vs process context**
  - In process context following a syscall/an exception
  - In interrupt context upon a hardware interrupt reception
- In interrupt context, **sleeping/blocking is not possible**
  - The handler is not a schedulable entity (user/kernel thread)
  - No `kmalloc(x, GFP_KERNEL)`
    - Use `GFP_ATOMIC`
  - No use of blocking synchronization primitives (ex: mutex)
    - Use spinlocks
- Interrupt context is **time-critical**
  - Other code is interrupted
- Interrupt handler stack:
  - Before 2.6: handlers used the kernel stack of the interrupted process
  - Later: 1 dedicated stack per core for handlers (1 page)

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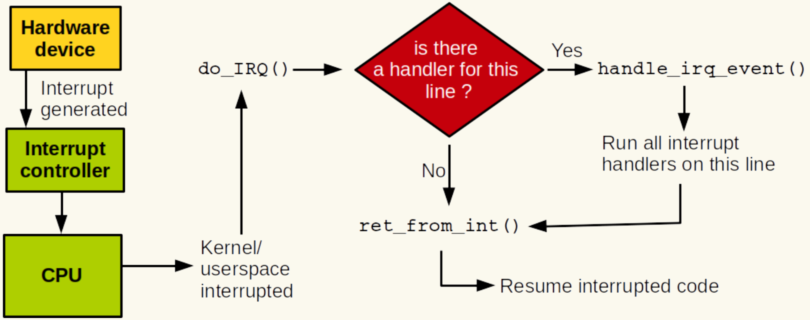
Interrupt handling internals in Linux

Interrupt processing path



- Taken from the textbook

Interrupt handling internals in Linux

Interrupt processing path (2)

- Specific entry point for each interrupt line
  - Saves the interrupt number and the current registers
  - Calls `do_IRQ()`
- `do_IRQ()`:
  - Acknowledge interrupt reception and disable the line
  - calls architecture specific functions
- Call chain ends up by calling `__handle_irq_event_percpu()`
  - Re-enable interrupts on the line if `IRQF_DISABLED` was not specified during handler registration
  - Call the handler if the line is not shared
  - Otherwise iterate over all the handlers registered on that line
  - Disable interrupts on the line again if they were previously enabled
- `do_IRQ()` returns to entry point that call `ret_from_intr()`
  - Checks if reschedule is needed (`need_resched`)
  - Restore register values

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/proc/interrupts

```
cat /proc/interrupts
           CPU0       CPU1     ...
  0:         19          0     ...     IR-IO-APIC    2-edge      timer
  1:          5          3     ...     IR-IO-APIC    1-edge      i8042
  8:          1          0     ...     IR-IO-APIC    8-edge      rtc0
  9:        272      13275     ...     IR-IO-APIC    9-fasteoi   acpi
 12:        387         11     ...     IR-IO-APIC   12-edge      i8042
 16:         24          2     ...     IR-IO-APIC   16-fasteoi   ehci_hcd:usb1
 23:         25          2     ...     IR-IO-APIC   23-fasteoi   ehci_hcd:usb2
```

- Columns:
  1. **Interrupt line** (not showed if no handler installed)
  2. **Per-cpu occurrence count**
  3. **Related interrupt controller name**
  4. **Edge/level (fasteoi)**: way the interrupt is triggered
  5. **Associated device name**

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Interrupt control

- Kernel code sometimes needs to **disable interrupts to ensure atomic execution** of a section of code
  - I.e. we don't want some code section to be interrupted by a handler (as well as kernel preemption)
  - The kernel provides an API to disable/enable interrupts:
    - Disable interrupts for the current CPU
    - Mask an interrupt line for the entire machine
- Note that *disabling interrupts does not protect against concurrent access from other cores*
  - Need locking, often used in conjunction with interrupts disabling

Interrupt control

Disabling interrupts on the local core

```
local_irq_disable();
/* ... */
local_irq_enable();
```

- **`local_irq_disable()` should never be called twice** without a `local_irq_enable()` between them
  - What if that code can be called from two locations:
    1. One with interrupts disabled
    2. One with interrupts enabled
- Need to save the interrupts state in order not to disable them twice:

```
unsigned long flags;

local_irq_save(flags);    /* disables interrupts _if needed_ */
/* .. */
local_irq_restore(flags); /* restores interrupts to the previous state */
/* flags is passed as value but both functions are actually macros */
```

Interrupt control

Disabling / enabling a specific interrupt line

- **Disable / enable a specific interrupt for the entire system**

```
void disable_irq(unsigned int irq);         /* (1) */
void disable_irq_nosync(unsigned int irq); /* (2) */
void enable_irq(unsigned int irq);          /* (3) */
void synchronize_irq(unsigned int irq);     /* (4) */
```

1. Does not return until any currently running handler finishes
2. Do not wait for handler termination
3. Enables interrupt line
4. Wait for a specific line handler to terminate before returning

- These enable/disable calls can nest
  - Must enable as much times as the previous disabling call number
- These functions do not sleep
  - They can be called from interrupt context

Interrupt control

Querying the status of the interrupt system

- **`in_interrupt()`** returns nonzero if the calling code is in interrupt context
  - Handler or bottom-half
- **`in_irq()`** returns nonzero only if in a handler
- To check if the code is in **process context:**
  - `!in_interrupt()`

Additional information

- Interrupts:
  - http://www.mathcs.emory.edu/~jallen/Courses/355/Syllabus/6-io/0-External/interupt.html
- More details on Linux interrupt management (v3.18):
  - https://0xax.gitbooks.io/linux-insides/content/interrupts/

Bibliography I

[1] Exceptions - osdev wiki.
http://wiki.osdev.org/Exceptions.
Accessed: 2017-02-08.

[2] X86 assembly/programmable interrupt controller.
https://en.wikibooks.org/wiki/X86_Assembly/Programmable_Interrupt_Controller.
Accessed: 2017-02-08.