Linux Kernel
Interrupt Handling

Paul Chu

Hao-Ran Liu

Interrupt Basics

- What is interrupt
  - A communication mechanism for hardware components to notify CPU of events. E.g. key strokes and timers.
  - There may be one or more interrupt request lines (IRQ), which is a physical input to the interrupt controller chip. The number of such inputs is limited. (eg. Classic PC has only 15 IRQ lines)
  - Each IRQ has a unique number, which may be used by one or more components.
- Basic flow of interrupt handling
  - When receiving an interrupt, CPU program counter jumps to a pre-defined address (interrupt vectors)
  - The state of interrupted program is saved
  - The corresponding service routine is executed
  - The interrupting component is served, and interrupt signal is removed
  - The state of interrupted program is restored
  - Resume the interrupted program at the interrupted address

Interrupts and Exceptions

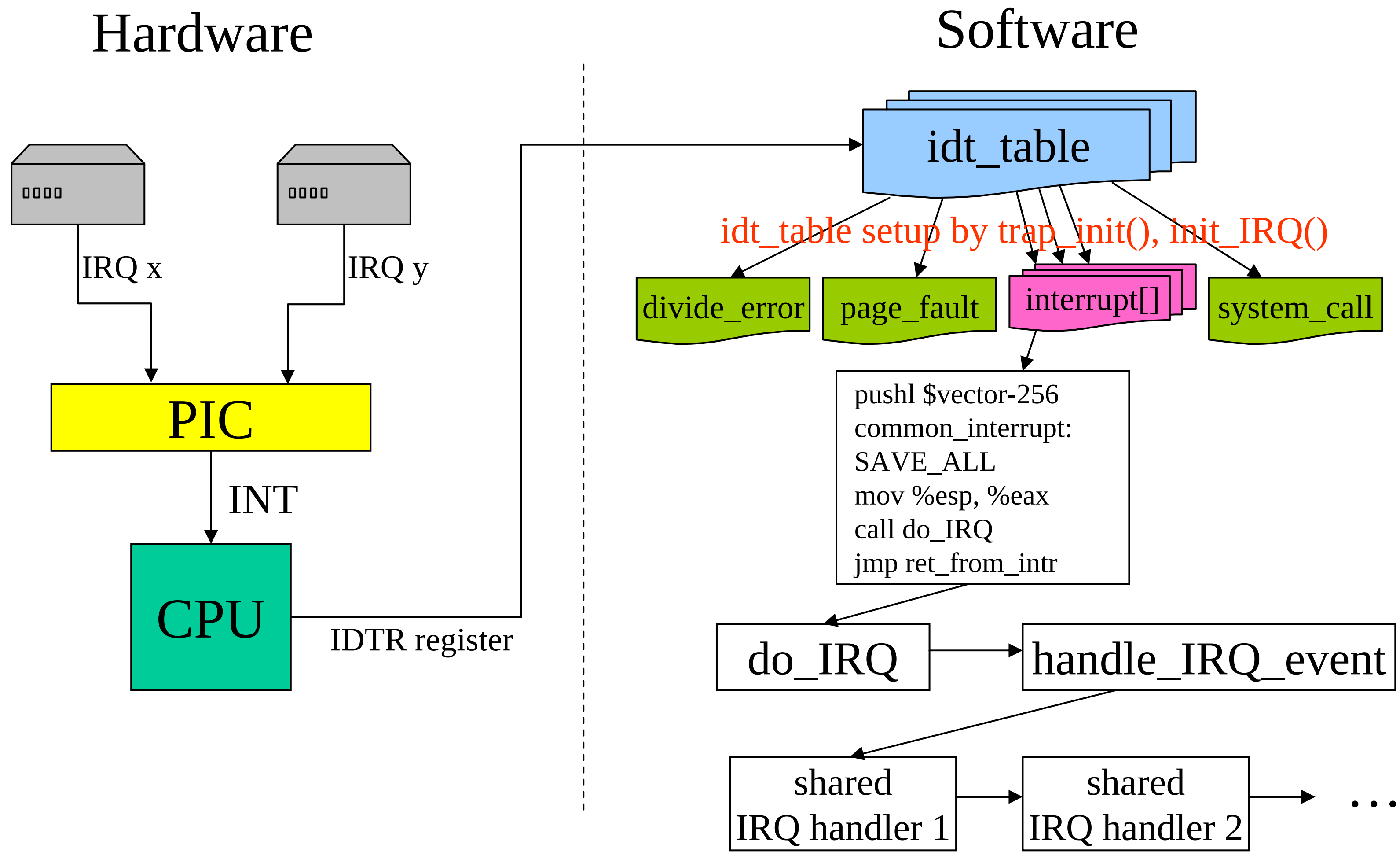
- Interrupts and exceptions are handled by the kernel in a similar way
- Interrupts
  - Asynchronous events generated by external hardware,
  - Interrupt controller chip maps each IRQ input to an interrupt vector, which locates the corresponding interrupt service routine
- Exceptions (Trap)
  - Synchronous events generated by the software
  - E.g. divide by zero, page faults

Interrupt vectors on x86

Vector range	Use
0-19 (0x0-0x13)	Nonmaskable interrupts and exceptions
20-31 (0x14-0x1f)	Intel-reserved
32-127 (0x20-0x7f)	External interrupts (IRQs)
128 (0x80)	Programmed exception for system calls
129-238 (0x81-0xee)	External interrupts (IRQs)
239 (0xef)	Local APIC timer interrupt
240-250 (0xf0-0xfa)	Reserved by Linux for future use
251-255 (0xfb-0xff)	Interprocessor interrupts

The table is from Understanding the Linux kernel, 2nd edition

Interrupt handling in x86 Linux



IRQ descriptors

- Each IRQ line is associated with an IRQ descriptor

```
typedef struct irq_desc {
    unsigned int status;              /* IRQ status: in progress, disabled, ... */
    hw_irq_controller *handler;       /* ack, end, enable, disable irq on PIC */
    struct irqaction *action;         /* IRQ action list */
    unsigned int depth;               /* nested irq disables */
    spinlock_t lock;                  /* serialize access to this structure */
} ____cacheline_aligned irq_desc_t;

irq_desc_t irq_desc[NR_IRQS] __cacheline_aligned = {
        [0 … NR_IRQS-1] = {
                .handler = &no_irq_type,
                .lock = SPIN_LOCK_UNLOCKED
        }
};
```

status field of the IRQ descriptor

Flag name	Description
IRQ_INPROGRESS	A handler for the IRQ is being executed.
IRQ_DISABLED	The IRQ line has been deliberately disabled by a device driver.
IRQ_PENDING	An IRQ has occurred on the line; its occurrence has been acknowledged to the PIC, but it has not yet been serviced by the kernel.
IRQ_AUTODETECT	The kernel uses the IRQ line while performing a hardware device probe.
IRQ_WAITING	The kernel uses the IRQ line while performing a hardware device probe; moreover, the corresponding interrupt has not been raised.

The table is from Understanding the Linux kernel, 2nd edition

Interrupt controller descriptor

- This describes operations of a interrupt controller

```
struct hw_interrupt_type {
 /* the name of the PIC, shown in /proc/interrupts */
   const char * typename;
   /* called at first time reg. of the irq */
   unsigned int (*startup)(unsigned int irq);
   /* called when all handlers on the irq unreg'ed */
   void (*shutdown)(unsigned int irq);

   void (*enable)(unsigned int irq); /* enable the specified IRQ */
   void (*disable)(unsigned int irq); /* disable the specified IRQ */
   void (*ack)(unsigned int irq);      /* ack. (may disable) the received IRQ */
   void (*end)(unsigned int irq);      /* called at termination of IRQ handler */
   void (*set_affinity)(unsigned int irq, cpumask_t dest);
};
```

i8259A interrupt controller

- i8259A is the classic interrupt controller on x86

```
static struct hw_interrupt_type i8259A_irq_type = {
        "XT-PIC",
        startup_8259A_irq,
        shutdown_8259A_irq,
        enable_8259A_irq,
        disable_8259A_irq,
        mask_and_ack_8259A,
        end_8259A_irq,
        NULL
};
```

- mask_and_ack_8259A() acknowledges the interrupt on the PIC and **also disables the IRQ line**
- end_8259A_irq() **re-enables the IRQ line**

irqaction

- Multiple devices can share a single IRQ; each irqaction refers to a specific hardware device and its interrupt handler

```
struct irqaction {
   /* Points to the interrupt service routine for an I/O device */
   irqreturn_t (*handler)(int, void *, struct pt_regs *);
   /* Describes the relationships between the IRQ line and the I/O device */
   unsigned long flags;
   cpumask_t mask;
   /* the name of the device, shown in /proc/interrupts */
   const char *name;
   /* a private field for the device driver */
   void *dev_id;
   /* points to next irqaction which shared the same IRQ line */
   struct irqaction *next;
   int irq;                                    /* IRQ number */
   struct proc_dir_entry *dir;
};
```

Registering Interrupt Handler

- Requesting to be invoked when a specific IRQ is signaled

```
int request_irq( unsigned int irq, irq_handler_t *handler, long irqflags,
           const char* devname, void *dev_id)
```

- irqflags
  - SA_INTERRUPT: This is a fast interrupt. All local IRQs are disabled during handler execution
  - SA_SAMPLE_RANDOM: The timing of interrupts from this device are fed to kernel entropy pool. This is for kernel random number generator
  - SA_SHIRQ: the IRQ line can be shared among multiple devices
- devname: the name of the device used by /proc/interrupts
- dev_id
  - The unique identifier of a handler for a shared IRQ
  - The argument passed to the registered handler (E.g. private structure or device number of the device driver)
  - Can be NULL only if the IRQ is not shared

Unregistering interrupt handler

- Unregister a specified interrupt handler and disable the given IRQ line if this is the last handler on the line.

```
int free_irq( unsigned int irq, void *dev_id)
```

- If the specified IRQ is shared, the handler identified by the dev_id is unregistered

Probing Interrupt Line

- Problem to solve
  - Fail to register interrupt handler because of not knowing which interrupt line the device has been assigned to
  - Rarely to use on embedded systems or for PCI devices
- Probing procedure
  - Clear and/or mask the device internal interrupt
  - Enable CPU interrupt
  - mask = probe_irq_on()
    - return a bit mask of unallocated interrupts
  - Enable device's interrupt and make it to trigger an interrupt
  - Busy waiting for a while allowing the expected interrupt to be signaled
  - irqs = probe_irq_off(mask)
    - Returns the number of the IRQ that was signaled
    - If no intterrupt occurred, 0 is returned; if more than 1 interrupt occurred, a negative value is returned
  - Service the device and clear pending interrupt

Writing an Interrupt Handler

- Handler prototype

```
int irqreturn_t handler(int irq, void *dev_id, struct pt_regs *regs);
```

  - dev_id: the dev_id you register at request_irq()
  - pt_regs: value of registers before being interrupted
- Return value
  - IRQ_NONE: the handler cannot handle it; the originator may be other devices sharing the same IRQ line
  - IRQ_HANDLED: the interrupt is serviced by the handler
  - IRQ_RETVAL(x): if x is nonzero, return IRQ_HANDLED; otherwise, return IRQ_NONE
- Interrupt handler is not reentrant; while it is executing:
  - its IRQ line is disabled on PIC
  - IRQ_INPROGRESS flag prevents other CPU from executing it

Interrupt handler sharing IRQ

- To share an IRQ with other device, you must
  - register_irq() with SA_SHIRQ flag
    - The registration fails if other handler already register the same IRQ without SA_SHIRQ flag
  - The dev_id argument must be unique to each handler
  - The interrupt handler must be able to find out whether its device actually generate an interrupt
    - Hardware must provide a status register for inquiry

Interrupt Handler Example

```
static ata_index_t do_ide_setup_pci_device (struct pci_dev *dev, ...) {
    hwif->irq = dev->irq;
}
```

```
#define ide_request_irq(irq,hand,flg,dev,id)  \
    request_irq((irq),(hand),(flg),(dev),(id))
static int init_irq (ide_hwif_t *hwif) {
    int sa = IDE_CHIPSET_IS_PCI(hwif->chipset)?SA_SHIRQ:SA_INTERRUPT;
    ide_request_irq(hwif->irq, &ide_intr, sa, hwif->name, hwgroup);
}
```

```
irqreturn_t ide_intr (int irq, void *dev_id, struct pt_regs *regs) {
    ide_hwgroup_t *hwgroup = (ide_hwgroup_t *)dev_id;
    ide_drive_t *drive = choose_drive(hwgroup);
    struct request *rq;

    rq = elv_next_request(drive->queue);
    start_request(drive, rq);
    return IRQ_HANDLED;
}
```

Interrupt Context

- Context
  - The execution environments of a piece of code
- Process context
  - Kernel is executing on behalf of a process. E.g. executing a system call.
  - Because of process management mechanisms, code in process context can sleep or be blocked
- Interrupt context
  - Time critical; it must finish its job quickly because it may interrupts some real-time job (may be a process or another interrupt handler)
  - No backing process; interrupted process context cannot be used
  - Code in interrupt context cannot sleep or be blocked (i.e. you cannot call some kernel functions that may sleep)
  - Configurable stack: dedicated interrupt stack (4K) or sharing the kernel stack of interrupted process (<8K)
  - Both interrupt handlers and bottom halves (softirq, tasklet) run in interrupt context

Implementation of Interrupt Handling -- do_IRQ()

- Interrupt context is not preemptive; preemption are disabled by increasing preempt_count
- Process softirq only when are not in interrupt context
  - Nested execution of interrupt handlers is possible

```
#define HARDIRQ_OFFSET          (1UL << HARDIRQ_SHIFT)
# define IRQ_EXIT_OFFSET        (HARDIRQ_OFFSET-1)
#define irq_enter()             (preempt_count() += HARDIRQ_OFFSET)
void irq_exit(void) {
        preempt_count() -= IRQ_EXIT_OFFSET;
        if (!in_interrupt() && local_softirq_pending()) do_softirq();
        preempt_enable_no_resched();
}
fastcall unsigned int do_IRQ(struct pt_regs *regs) {
        int irq = regs->orig_eax & 0xff;
        irq_enter();
        __do_IRQ(irq, regs);
        irq_exit();
        return 1;
}
```

Implementation of Interrupt Handling -- __do_IRQ()

- IRQ Probing
  - probe_irq_on() set IRQ_WAITING for all unallocated IRQs
  - IRQ_WAITING flag is cleared when interrupt signals
  - probe_irq_off() checks this flag to find the IRQ number of expected interrupt

```
fastcall unsigned int __do_IRQ(unsigned int irq, struct pt_regs *regs)
{
        irq_desc_t *desc = irq_desc + irq;
        struct irqaction * action;
        unsigned int status;

         /* avoid concurrent execution of the same IRQ */
        spin_lock(&desc->lock);
        desc->handler->ack(irq); /* disable IRQ at PIC */
        status = desc->status & ~IRQ_WAITING;
        status |= IRQ_PENDING; /* we _want_ to handle it */
```

Implementation of Interrupt Handling -- __do_IRQ()

- IRQ_INPROGRESS flag prevents handlers of the same IRQ from concurrent execution

```
action = NULL;
if (likely(!(status & (IRQ_DISABLED | IRQ_INPROGRESS)))) {
        action = desc->action;
        status &= ~IRQ_PENDING; /* we commit to handling */
        status |= IRQ_INPROGRESS; /* we are handling it */
}
desc->status = status;
/*
 * If there is no IRQ handler or it was disabled, exit early.
 * Since we set PENDING, if another processor is handling
 * a different instance of this same irq, the other processor
 * will take care of it.
 */
if (unlikely(!action)) goto out;
```

Implementation of Interrupt Handling -- __do_IRQ()

- Take care of other CPUs' interrupt by checking IRQ_PENDING flag

```
        for (;;) {
                irqreturn_t action_ret;
                spin_unlock(&desc->lock);
                action_ret = handle_IRQ_event(irq, regs, action);
                spin_lock(&desc->lock);
                if (likely(!(desc->status & IRQ_PENDING)))
                        break;
                desc->status &= ~IRQ_PENDING;
        }
        desc->status &= ~IRQ_INPROGRESS;
out:
        desc->handler->end(irq);  /* enable IRQ at PIC */
        spin_unlock(&desc->lock);
        return 1;
}
```

Implementation of Interrupt Handling -- handle_IRQ_event()

- Invoke all registered handlers of the IRQ line since kernel do not know the origin of the signaled interrupt

```
fastcall int handle_IRQ_event(unsigned int irq, struct pt_regs *regs,
                                            struct irqaction *action) {
          int ret, retval = 0, status = 0;

          if (!(action->flags & SA_INTERRUPT))
                    local_irq_enable();          /* fast interrupt */
          do {
                    ret = action->handler(irq, action->dev_id, regs);
                    if (ret == IRQ_HANDLED)
                              status |= action->flags;
                    retval |= ret;
                    action = action->next;
          } while (action);
          if (status & SA_SAMPLE_RANDOM)
                    add_interrupt_randomness(irq);
          local_irq_disable();
          return retval;
}
```

Implementation of Interrupt Handling -- ret_from_intr()

- Before returning to the interrupted context, call schedule() for a reschedule when:
  - The kernel is returning to user space and need_resched() is true
  - The kernel is returning to kernel space and preempt_count() is zero
- The value of registers are restored and the kernel resumes whatever was interrupted

References

- Linux Kernel Development, 2nd Edition, Robert Love, 2005
- Understanding the Linux Kernel, Bovet & Cesati, O'REILLY, 2002
- Linux 2.6.10 kernel source