Lecture 21: Interrupt Handling

Fall 2019

Jason Tang

Slides based upon Linux Device Drivers, 3rd Edition
http://lwn.net/Kernel/LDD3/

Topics

- Hardware Interrupts
- Linux Interrupt Handling
- Writing Interrupt Handlers
- Top-Half / Bottom-Half Design

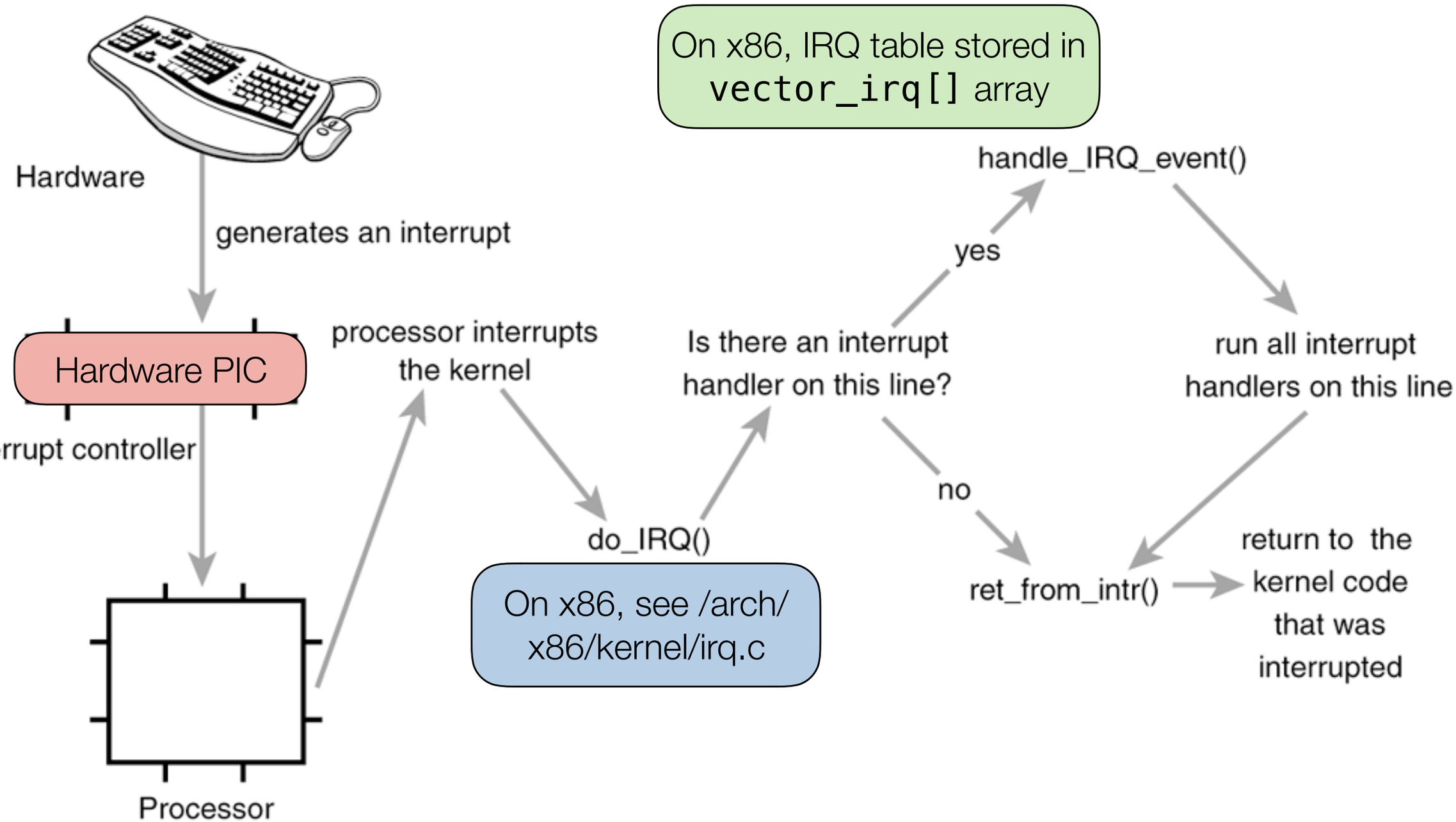
Hardware Interrupts

- Real device drivers have to deal with real hardware
- Device drivers usually written using event-based design:
  - Driver installs callbacks, and then enables hardware
- Hardware generates interrupts asynchronously
- Callbacks invoked to handle (or service) that interrupt

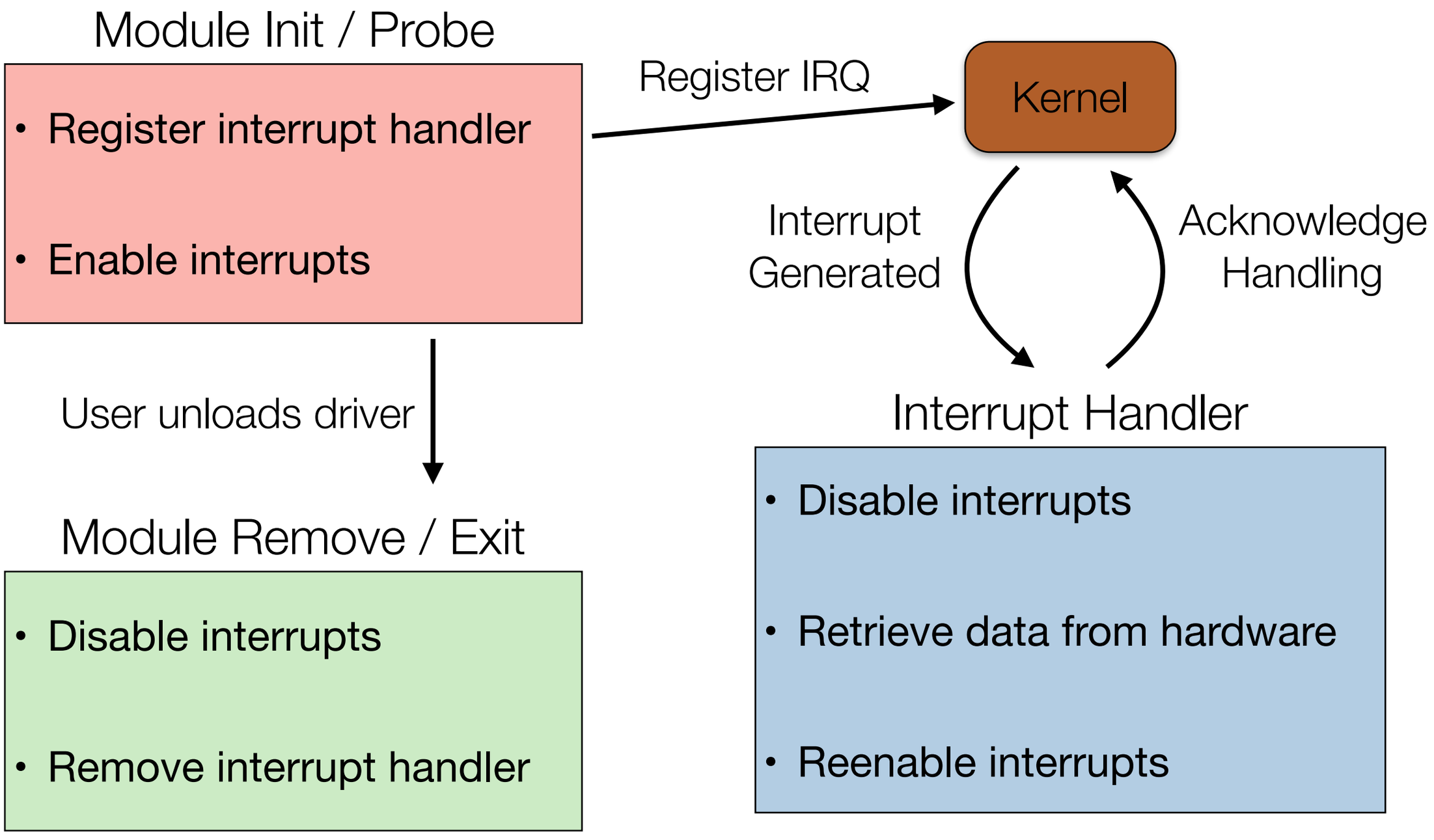
IRQ Handling

- A hardware device sends an electrical signal on a physical interrupt line
- Processor detects that signal and translates it into an interrupt request (IRQ) number
- Processor then jumps to kernel's interrupt handling code
- Kernel searches through its interrupt request table (stored in RAM) for entry or entries that match the IRQ
- If found, kernel jumps to the interrupt service routine (ISR) that was registered
- If not found, kernel ignores IRQ

IRQ Handling



Interrupt Handling Overview



Linux Interrupt Handling

```
int request_irq(unsigned int irq, irq_handler_t handler,
                unsigned long flags, const char *name, void *dev);
```

- Declared in include/linux/interrupt.h
- First parameter is which IRQ number to register
- Second parameter is a function pointer to invoke upon interrupt reception
- Third parameter is flag(s) when registering IRQ (often set to 0)
- Fourth parameter is a free-form name for ISR
- Fifth parameter is the ISR cookie
- Returns 0 on success, negative on error

Example Interrupt Registration

```
if (request_irq(HP680_TS_IRQ, hp680_ts_interrupt,
                0, MODNAME, NULL) < 0) {
    printk(KERN_ERR "hp680_touchscreen.c: Can't allocate irq %d\n",
           HP680_TS_IRQ);
    err = -EBUSY;
    goto fail1;
}
```

From drivers/input/touchscreen/hp680_ts_input.c

- String given as fourth parameter is the one shown in `/proc/interrupts`:

```
$ cat /proc/interrupts
           CPU0       CPU1       CPU2       CPU3
  0:         47          0          0          0   IO-APIC-edge      timer
  1:       1818          0          0          0   IO-APIC-edge      i8042
  6:         38         27         27         18   IO-APIC-edge
  8:          0          0          0          0   IO-APIC-edge      rtc0
  9:          0          0          0          0   IO-APIC-fasteoi   acpi
 12:        733          0          0          0   IO-APIC-edge      i8042
```

IRQ number

Number of times ISR was invoked

Name of ISR

Example ISR

```
static irqreturn_t hp680_ts_interrupt(int irq, void *dev)
{
    disable_irq_nosync(irq);
    schedule_delayed_work(&work, HZ / 20);

    return IRQ_HANDLED;
}
```

- First parameter to ISR is IRQ number that raised interrupt
- Second parameter is the cookie (and was the last parameter to `request_irq()`)
- Return value is of type `irqreturn_t` (declared in include/linux/irqreturn.h)
  - `IRQ_NONE`: interrupt was not from this device (used when sharing IRQs)
  - `IRQ_HANDLED`: interrupt was handled by this device

Example Interrupt Freeing

```
static void __exit hp680_ts_exit(void)
{
    free_irq(HP680_TS_IRQ, NULL);
    cancel_delayed_work_sync(&work);
    input_unregister_device(hp680_ts_dev);
}
```

- First parameter to `free_irq()` is IRQ number (first parameter to `request_irq()`)
- Second parameter is the cookie (last parameter to `request_irq()`)
- If module does not unregister ISR, kernel will panic when interrupt is raised
  - Make sure ISRs are removed in module init/probe error paths

ISR Cookies

- Use cookies to identify which hardware instance corresponds to which IRQ handler, in case the driver is handling multiple instances of that hardware

- Cookie is usually the return value from `kmalloc()` (the device private data)

```
static int ili210x_i2c_probe(struct i2c_client *client,
                             const struct i2c_device_id *id)
{
    /* ... */
    struct ili210x *priv;
    /* ... */
    priv = kzalloc(sizeof(*priv), GFP_KERNEL);
    /* ... */
    error = request_irq(client->irq, ili210x_irq, pdata->irq_flags,
                        client->name, priv);
}
```

From drivers/input/touchscreen/ili210x.c

Writing Interrupt Handlers

- While kernel is servicing interrupt, no other useful work is occurring
- Also while within ISR, that CPU is unable to handle additional incoming interrupts
  - May miss interrupts, especially when running a real-time system
  - ISRs must finish quickly
- CPU disables preemption just before it jumps into interrupt handling code
  - ISRs run in interrupt context, as compared to process context

Interrupt Context

- While running in interrupt context, ISR cannot be preempted (on that CPU)
- ISR **may not** call functions that can sleep:
  - `kmalloc()` with `GFP_KERNEL` (**must** instead use `GFP_ATOMIC`)
  - `mutex_lock()`
  - `schedule_timeout()`
- **Calling any sleeping function will usually cause a kernel deadlock**

Top-Half / Bottom-Half

- As that ISR must run fast and runs in interrupt context, common pattern is to divide interrupt handling into two parts

- Top-Half: routine that responds to interrupt, running in interrupt context
    - Acknowledges interrupt
    - Wakes up a kthread to finish servicing interrupt
- Bottom-Half: routine that does actual work (delayed work)
    - As that it is a kthread, it runs in process context

Threaded Interrupt Handling

```
int request_threaded_irq(unsigned int irq,
                         irq_handler_t handler,
                         irq_handler_t thread_fn,
                         unsigned long flags, const char *name,
                         void *dev);
```

- Like `request_irq()`, but with additional parameter `thread_fn`

- If the `handler` function (top-half) returns `IRQ_WAKE_THREAD`, then kernel will automatically schedule a kthread to run `thread_fn` (bottom-half)

  - Top-half should disable interrupts on that device

  - Bottom-half should reenable interrupts after it has finished running

Example Threaded Interrupt Registration

```
err = request_threaded_irq(dev->dev->irq, b43_interrupt_handler,
                           b43_interrupt_thread_handler,
                           IRQF_SHARED, KBUILD_MODNAME, dev);
if (err) {
    b43err(dev->wl, "Cannot request IRQ-%d\n",
           dev->dev->irq);
    goto out;
}
```

From drivers/net/wireless/b43/main.c

- Register threaded interrupt handler similarly as `request_irq()`, with addition of parameter that specifies bottom-half

- Just like `request_irq()`, driver must call `free_irq()` at module exit / remove and also within error handling code in module init/probe

Example Top-Half

```
static irqreturn_t b43_interrupt_handler(int irq, void *dev_id)
{
    struct b43_wldev *dev = dev_id;
    irqreturn_t ret;

    if (unlikely(b43_status(dev) < B43_STAT_STARTED))
        return IRQ_NONE;

    spin_lock(&dev->wl->hardirq_lock);
    ret = b43_do_interrupt(dev);
    mmiowb();
    spin_unlock(&dev->wl->hardirq_lock);

    return ret;
}
```

This function returns `IRQ_NONE` or `IRQ_WAKE_THREAD`

- The top-half returns `IRQ_NONE` if this driver is not handling interrupt, `IRQ_HANDLED` if it finished handling interrupt, or `IRQ_WAKE_THREAD` to continue processing within a bottom-half

Example Bottom-Half

```
static irqreturn_t b43_interrupt_thread_handler(int irq, void *dev_id)
{
    struct b43_wldev *dev = dev_id;

    mutex_lock(&dev->wl->mutex);
    b43_do_interrupt_thread(dev);
    mmiowb();
    mutex_unlock(&dev->wl->mutex);

    return IRQ_HANDLED;
}
```

- Parameters to bottom-half same as parameters to top-half
- Bottom-half returns `IRQ_HANDLED` when it has finished its work
- **Because bottom-half is running in process context, it may use mutexes and call other functions that can sleep**

Spinlocks and Interrupt Handlers

- Spinlocks are safe to use in top-halves as that they do not sleep
- **May be dangerous** for a kthread to hold a spinlock that a top-half also needs
  - Deadlock will occur if top-half is blocked on a single-processor system
- Solution is for kthread to ensure that top-half will not deadlock, even if spinlock already held
- Use special form `spin_lock_irqsave()`
  - **Must use this form whenever same spinlock can be held in both interrupt and process context**

Spinlocks and Interrupt Handlers

```
void spin_lock_irqsave(spinlock_t *lock, unsigned long flags);
void spin_unlock_irqrestore(spinlock_t *lock, unsigned long flags);
```

- `spin_lock_irqsave()` acquires spinlock, saves the current state in `flags`, and disables interrupts on that CPU

- `spin_unlock_irqrestore()` releases spinlock, then reenables interrupts

```
static inline unsigned char rtc_is_updating(void)
{
    unsigned long flags;
    unsigned char uip;

    spin_lock_irqsave(&rtc_lock, flags);
    uip = (CMOS_READ(RTC_FREQ_SELECT) & RTC_UIP);
    spin_unlock_irqrestore(&rtc_lock, flags);
    return uip;
}
```

From drivers/char/rtc.c

Threaded Interrupt Handling Summary