Lecture 5: Interrupts & Time

[RTCS Ch. 5]

- interrupts
- clock interrupts
- time primitives
- periodic processes

External Communication

A real-time system must communicate with the environment:

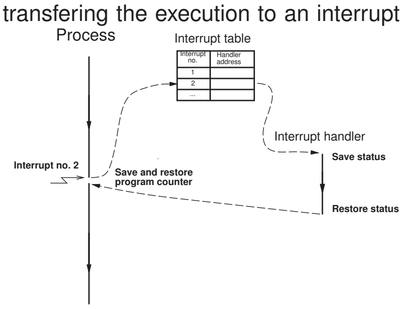
- A/D and D/A converters
- serial and parallel ports
- keyboard and mouse
- bus interfaces
- timers

The communication can be based on

- polling
- interrupts

Interrupts

Interrupts are generated on the CPU hardware level, asynchronously transfering the execution to an interrupt handler.



The interrupt number is known as the interrupt request (IRQ)

The program counter is always saved and restored.

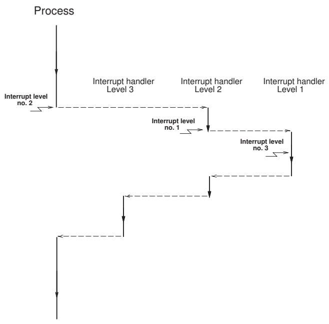
The interrupt handler is to save away and restore the registers it uses.

The context can be saved

- on the stack of the interrupted process
- on a special stack common to all interrupts
- in a specialized set of registers (DSPs, PowerPC, ...)

A context switch may be initiated from the interrupt handler. In this case the program counter will be restored to a different value.

Interrupt Priorities



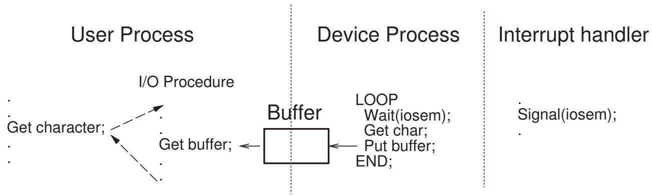
Disabling the interrupts in the kernel causes all interrupt levels to be disabled.

"Hardware priorities"

Only possible to store a limited number of pending interrupts.

Interrupt handlers need to be short and efficient.

Time consuming processing in device processes.



Problem: two full context switches needed

Tick-Based vs Event-Based Kernels

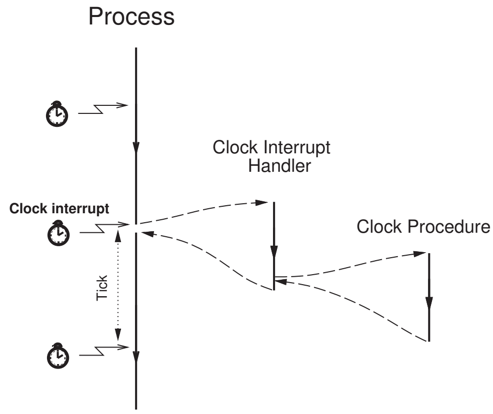
Most real-time kernels are **tick-based**:

- A system clock gives interrupts at regular intervals
- Typical tick intervals are 1 ms, 10 ms
- Defines the time resolution of the kernel

An **event-based** kernel relies on a high-precision timer to keep track of time.

- No regular clock interrupts

Clock Interrupts



Clock Procedure

```
PROCEDURE Clock;
VAR P: ProcessRef;
BEGIN
  IncTime(Now,Tick); (* Now := Now + Tick *)
  LOOP
    P := TimeQueue^.succ;
    IF CompareTime(P^.head.nextTime,Now) <= 0 THEN
      MovePriority(P,ReadyQueue);
    ELSE EXIT;
    END;
  END;
  DEC(Running^.timer); (* Round-robin time slicing *)
  IF Running^.timer <= 0 THEN
    MovePriority(Running,ReadyQueue);
  END;
  Schedule;
END Clock;
```


Clock Procedure

`Now` is a global variable that keeps track of the current time.

`TimeQueue` is a time-sorted list containing processes waiting on time.

Round-robin time-slicing within the same priority levels:

- if a process has executed longer than its time slice and other processes with the same priority are ready then a context switch takes place
- used by the Linux real-time scheduling class SCHED_RR

The Linux real-time scheduling class SCHED_FIFO does not use round-robin within the same priority levels.

Event-Based Clock Interrupts

Clock interrupts from a variable time source (e.g. high-resolution timer) instead of a fixed clock.

When a process is inserted in `TimeQueue` the kernel sets up the timer to give an interrupt at the wake-up time of the first process in `TimeQueue`.

When the clock interrupt occurs, a context switch to the first process is performed and the timing chip is set up to give an interrupt at the wake-up time of the new first process in `TimeQueue`.

Interrupts and Java

In the native-thread model each Java thread is mapped onto a separate native thread ⇒ nothing is different

In the green-thread model things become more complicated

- The system level interrupt handling facility has no notion of Java threads
- when a Java thread performs a blocking operation the JVM indicates that it wants to be informed by the operating system when the associated IO interrupt occurs.
- The JVM Linux thread does not block until it has serviced all Java threads that are Ready.
- When no Java threads are Ready, the JVM thread does a selective wait (multiplexed IO) on all the IO interrupts that it needs to be informed about. A timeout is set to the time when the next sleeping Java thread should execute.

Interrupt Handling in Linux

Interrupt handler is known as the Interrupt Service Routine (ISR)

The conflicting goal of having ISRs that both execute fast *and* perform a lot of work is solved by splitting them in two halves:

- the top half (the actual interrupt handler)
- the bottom half
  - executes at later stage (deferred until later)
  - executes in a similar way as an ordinary taskm but is more efficient, e.g., has a smaller context
  - compare with device processes
  - supported in multiple ways
    - softirq
    - tasklet
    - work queue

Exceptions

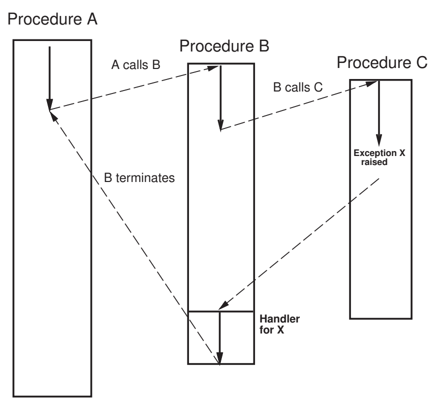
Many modern programming languages support software fault handling using exceptions.

When a fault occurs in a piece of code, an exception is raised (or thrown).

The run-time system locates the closest handler for the exception and transfers the execution to it.

Many similarities with interrupts:

- exceptions occur synchronously w.r.t. the processor clock, i.e. they can be seen as synchronous interrupts generated by the processor
- interrupts = asynchronous interrupts generated by the hardware



Exception Handling in Java

```
try {
  // Perform some method calls that
  // might throw exceptions
} catch (Exception e) {
  // Control transfered here if there
  // is an exception. Handle the fault
} finally {
  // These lines are always executed. Clean-up
}
```

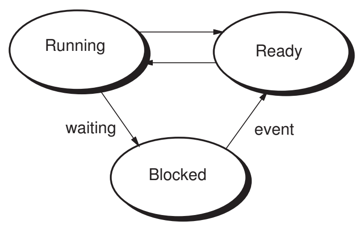

Wait Time Primitives

Two main types:

- Wait a time interval
  - relative to current time
  - sleep (Java), delay (Ada), WaitTime (STORK)
- Wait until a specified time
  - absolute time
  - delayuntil (Ada), WaitUntil (STORK)
  - unfortunately not available in Java

WaitUntil primitives more powerful

Wait Time and Process States



When WaitTime/WaitUntil is called: process moved from Running to Blocked (moved from ReadyQueue to TimeQueue)

When time has passed: process moved from Blocked to Ready (done in the `Clock` procedure)

Time Primitives in STORK

```
PROCEDURE Tick(): CARDINAL;
```

Returns the tick interval of the current machine in milliseconds. This makes it possible to write real-time code that is portable between platforms with different time resolution.

```
PROCEDURE CurrentTime(VAR t: Time);
```

Returns the current time (`Now`).

```
PROCEDURE IncTime(VAR t: Time, c: CARDINAL);
```

Increments the value of `t` with `c` milliseconds.

```
PROCEDURE CompareTime(VAR t1,t2: TIME): INTEGER;
```

Compares two time variables. Returns -1 if $t1 < t2$. Returns 0 if $t1 = t2$. Returns 1 if $t1 > t2$.


```
PROCEDURE WaitUntil(t: Time);
```

Delays the calling process until $Now \geq t$. If `Now` is already larger than `t` when `WaitUntil` is called it is a null operation.

```
PROCEDURE WaitTime(t: CARDINAL);
```

Delays the calling process for `t` milliseconds.

Implementation

```
PROCEDURE WaitUntil(t: Time);
BEGIN
  Running^.head.nextTime := t;
  MoveTime(Running,TimeQueue);
  Schedule;
END WaitUntil;


PROCEDURE WaitTime(t: CARDINAL);
VAR next: Time;
BEGIN
  CurrentTime(next);
  IncTime(next,t);
  WaitUntil(next);
END WaitTime;
```


Time Primitives in Java

No WaitUntil, only WaitTime (sleep).

Methods:

- `sleep(long milliseconds)`: Puts the currently executing thread to sleep for (at least) the specified number of milliseconds. Static method of the `Thread` class.
- `currentTimeMillis()`: Returns the current time in milliseconds. Static method of the `System` class.

The Idle process

What to do when all processes are blocked?

1. The CPU contains no other processes
   - Idle process at lowest priority

```
(* Process *) PROCEDURE Idle;
BEGIN
  SetPriority(MaxPriority - 1);
  LOOP END;
END Idle;
```

2. The CPU contains other non-realtime processes
   - the whole process waits until the wakeup time of the first process in `TimeQueue`

Implementing Periodic Tasks

Periodic tasks are very common in real-time systems.

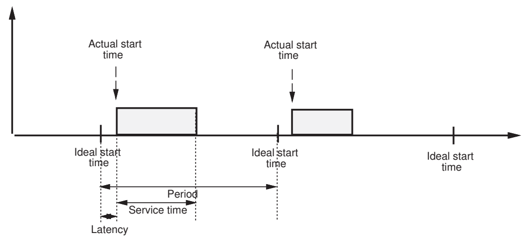
Implementation options without a real-time kernel:

- Implement each periodic activity in an interrupt handler associated with a periodic timer.
  - Only limited number of timers
  - Difficult, error-prone
- Use a static cyclic executive
  - Scheduler driven by periodic timer
  - Inflexible

Implementation options using a real-time kernel:

- Real-time kernel with wait time primitives:
  - Self-scheduling tasks (infinite loops with wait statements)
- Real-time kernel with explicit support for periodic tasks:
  - Allows the programmer to register a function in the kernel to be executed every T seconds
  - Not common

Periodic Execution



- Latency: Release jitter due to limited time precision (e.g. tick scheduling) and preemption from higher-priority tasks
- Service time: Actual execution time and preemption from higher-priority tasks

Implementing Self-Scheduling Periodic Tasks

Attempt 1:

```
LOOP
  PeriodicActivity;
  WaitTime(h);
END;
```

Does not work.

Period $> h$ and time-varying.

The execution time of PeriodicActivity is not accounted for.

Implementing Self-Scheduling Periodic Tasks

Attempt 2:

```
LOOP
  CurrentTime(Start);
  PeriodicActivity;
  CurrentTime(Stop);
  C := Stop - Start;
  WaitTime(h - C);
END;
```

Does not work.

An interrupt causing suspension may occur between the assignment and WaitTime. Need a WaitUntil primitive.

Implementing Self-Scheduling Periodic Tasks

Attempt 3:

```
LOOP
  CurrentTime(t);
  PeriodicActivity;
  IncTime(t,h);
  WaitUntil(t);
END;
```

Does not work.

Preemption by a higher-priority task may delay CurrentTime from being executed.

Implementing Self-Scheduling Periodic Tasks

Attempt 4:

```
CurrentTime(t);
LOOP
  PeriodicActivity;
  IncTime(t,h);
  WaitUntil(t);
END;
```

Correct.

Will however try to catch up if the actual execution time of PeriodicActivity occasionally becomes larger than the period.

Implementing Self-Scheduling Periodic Tasks

Attempt 5: Reset the base time in case of overruns. Accept a too long sample and try to be on time from now on.

Assume the existence of a new WaitTime primitive

```
PROCEDURE NewWaitUntil(VAR t: TIME) // VAR = call-by-reference
VAR diff : INTEGER;

BEGIN
  disableInterrupts;
  diff := CompareTime(t,Now);
  IF diff > 0 THEN
    Running^.head.nextTime := t;
    MoveTime(Running, TimeQueue);
    Schedule;
  ELSE
    CurrentTime(t);
  END;
  enableInterrupts;
END NewWaitUntil;
```


The code now becomes

```
CurrentTime(t);
LOOP
  PeriodicActivity;
  IncTime(t,h);
  NewWaitUntil(t);
END;
```


Self-Scheduling Periodic Tasks in Java

```
public void run() {
  long h = 10; // period (ms)
  long duration;
  long t = System.currentTimeMillis();

  while (true) {
    periodicActivity();
    t = t + h;
    duration = t - System.currentTimeMillis();
    if (duration > 0) {
      try {
        sleep(duration);
      } catch (InterruptedException e) {}
    }
  }
}
```


Foreground-Background Scheduler

Foreground tasks (e.g. controllers) execute in interrupt handlers.

The background task runs as the main program loop

A common way to achieve simple concurrency on low-end implementation platforms that do not support any real-time kernels.

Will be used in the ATMEL AVR projects in the course as well as in Lab 3.

Periodic Execution in the Atmel AVR mega16

Main program:

```
#include <avr/io.h>
#include <avr/signal.h>
#include <avr/interrupt.h>

int main() {
  TCNT2 = 0x00;   /* Timer 2: Reset counter (periodic timer) */
  TCCR2 = 0x0f;   /* Set clock prescaler to 1024             */
  OCR2 = 144;     /* Set the compare value, corr. to ~100 Hz
                     when clock runs @14.7 MHz               */

  outp(BV(OCIE2),TIMSK); /* Start periodic timer */
  sei();                 /* Enable interrupts */

  while (1) {
    /* Do some background work */
  }
}
```


Timer interrupt handler:

```
/**
 * Interrupt handler for the periodic timer.
 * Interrupts are generated every 10 ms. The
 * control algorithm is executed every 50 ms.
 */
SIGNAL(SIG_OUTPUT_COMPARE2) {
  static int8_t ctr = 0;   /* static to retain value
                              between invocations! */
  if (++ctr == 5) {
    ctr = 0;
    /* Run the controller */
  }
}
```