# Interrupts and Time

Real-Time Systems, Lecture 5

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## Content

[Real-Time Control System: Chapter 5]





## 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.

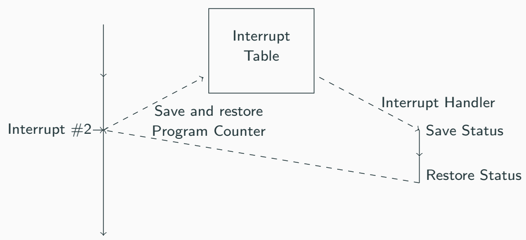
The communication can be based on (1) polling, (2) interrupts.



# Interrupts

## Interrupts

Interrupts are generated at the CPU hardware level, asynchronously. When an interrupt is generated the execution is transfered to an interrupt handler method.




The Interrupt Table contains a mapping between the Interrupt Number and the Interrupt Handler that should be called. The interrupt number is known as the Interrupt Request (IRQ).



## Interrupts

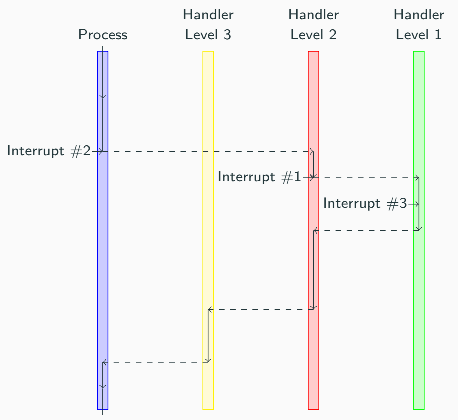
When an interrupt is received, the program counter is saved (and later restored). The interrupt handler saves all the status of the registers it uses and restore the status when it terminates.

The context can be saved:

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

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

## Interrupt Priorities






## Interrupt Priorities

Disabling the interrupts in the kernel causes all interrupt levels to be disabled (hardware priorities).

- It is only possible to store a limited number of pending interrupts.
- Interrupts handlers need to be short and efficient.
- Time consuming processing in device processes.



## Time-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.

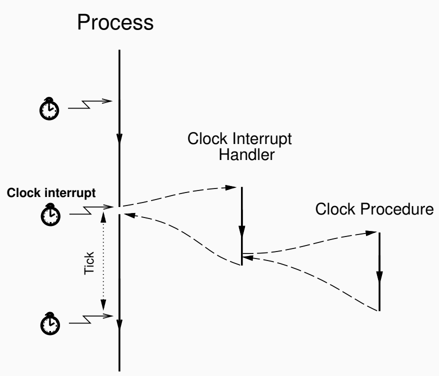
An **event-based** kernel relies on a high-precision timer to keep track of time:

- No regular clock interrupts.



# Clock Interrupts

## Clock Interrupts






## [STORK] 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;
```

## [STORK] 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`.



## [JAVA] Interrupts

In the native thread model each Java thread is mapped onto a separate thread. Essentially as in STORK.

In the green thread model:

- 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 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 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.



## [LINUX] Interrupts

The 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 task, but is more efficient, e.g., has a smaller context;
  - compare with device processes;
  - supported in multiple ways, like
    - 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).

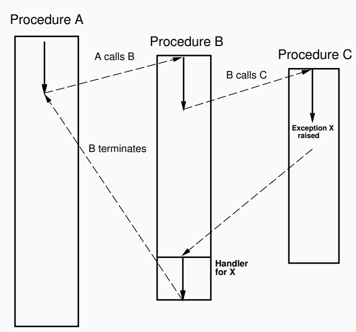
The run-time system locates the closest handler for the exception and transfers the execution to it.

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.



## Exceptions



## [JAVA] Exception Handling

```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.
}
```



## Time Primitives

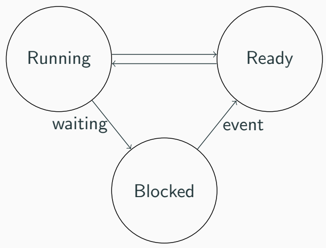
## Wait Time Primitives

Two main types:

- Wait for a specified time interval:
  - relative to current time;
  - sleep (Java), delay (Ada), WaitTime (STORK).
- Wait until a specified time (more powerful):
  - absolute time;
  - delayuntil (Ada), WaitUntil (STORK);
  - not available in Java.



## 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).



## [STORK] Time Primitives

`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.



## [STORK] Time Primitives

`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.

## [STORK] Time Primitives: 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;
```



## [JAVA] Time Primitives

There is no WaitUntil, only WaitTime (sleep).

Methods:

- `sleep(long milliseconds);`
  puts the currently executing thread to sleep for (at least) the specified amount of time. 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 the processes are blocked?

- The CPU contains no other processes. The Idle process (lowest priority) is executed.

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

- The CPU contains other non-real-time processes. Wait until the wakeup time of the first process in the `TimeQueue`.



## A complete real-time kernel

Real-Time kernel parts:

- how a process/thread/task is represented;
- what happens during a context switch;
- communication and synchronization mechanisms;
- interrupt handling;
- sleep;
- the idle process.



## A complete real-time kernel: Task Queues

- ReadyQueue:
  - one in the single-processor case or when using global scheduling for multicores;
  - multiple in case of partitioned scheduling for multicores;
  - sorted in priority order.
- TimeQueue:
  - sorted in earliest wakup time order.
- WaitQueues for semaphores, monitors, locks:
  - sorted in priority order.
- WaitQueues for threads waiting for event/condition variable:
  - normally sorted in priority order.



## Reasons for a context switch – 1

The running thread executes an operation that leads to a context switch.

- Voluntarily releases the CPU:
  - sleeps, the thread terminates, yields.
- Performs an operation that may cause it to block:
  - waits on semaphore, tries to take/lock a monitor.
- Performs an operation that unblocks another higher priority thread:
  - signals a semaphore, returns a lock.

## Reasons for a context switch – 2

Due to an interrupt.

- Clock interrupt:
  - a sleeping thread of higher priority than the executing one is woken up;
  - the running thread has executed longer than its time slice and there is another thread with the same priority that is ready to execute.
- Other types of interrupts, like bus, keyboard, mouse:
  - context switch to a device thread that handles the interrupt, which eventually may cause a context switch to a thread waiting for events like input/output ones.



## Periodic Tasks

## 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 period timer:
  - only limited number of timers;
  - difficult and error-prone.
- Use a static cyclic executive:
  - scheduler driven by period timer;
  - inflexible.



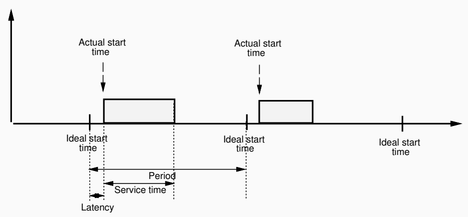
## Implementing Periodic Tasks

Implementation options with a real-time kernel:

- Real-Time kernel with wait time primitives:
  - self-scheduling tasks (infinite loop 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 Tasks




- Latency: Release jitter due to limited time precision (for example 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. The period is greater than $h$, and time-varying. The execution time of PeriodicActivity is not accounted for.

## Implementing Self-Scheduling Periodic Tasks

**Attempt 2**

```
LOOP
  CurrentTime(Start);
  PeriodicActivity;
  CurrentTime(Finish);
  Duration := Finish - Start;
  WaitTime(h - Duration);
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 that sample on.

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

BEGIN
  disableInterrupts;
  diff := CompareTime(t, Now);
  IF diff > 0 THEN // not overrun
    Running^.head.nextTime := t;
    MoveTime(Running, TimeQueue);
    Schedule;
  ELSE
    CurrentTime(t);
  END;
  enableInterrupts;
END NewWaitUntil;
END;
```



## Implementing Self-Scheduling Periodic Tasks

**Attempt 5**: the code becomes:

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



## [JAVA] Implementing Self-Scheduling Periodic Tasks

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

  while (true) {
    periodicActivity();
    t = t + h; // when it should be repeated
    duration = t - System.currentTimeMillis();
    if (duration > 0) {
      try {
        sleep(duration);
      } catch (InterruptedException e) { e.printStackTrace(); }
    }
  }
}
```

## Foreground-Background Scheduler

Foreground tasks (like 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 Lab3.



## 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               */
                  /* 14.7 MHz/1024/144 is approx 100 Hz      */

  outp(BV(OCIE2),TIMSK); /* Start periodic timer */
  sei();                 /* Enable interrupts */
  while (1) {
    /* Do some background work */
  }
}
```



## Periodic Execution in The ATMEL AVR mega16

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 */
  }
}
```