5. System issues

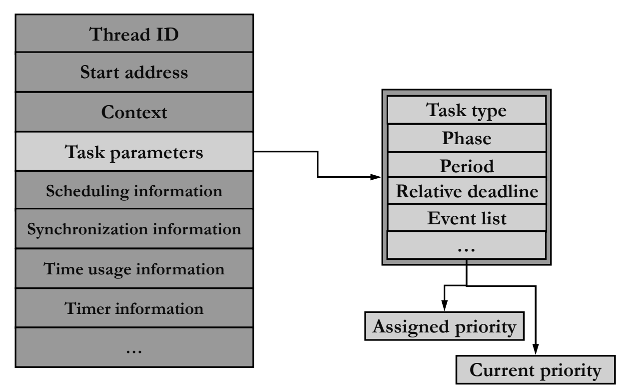
Context switch

- Preemption causes time and space overheads which should be duly accounted for in realistic schedulability tests
- Under preemption every single job incurs at least two context switches
  - One at activation to install its execution context
  - One at completion to clean up
- The resulting costs should be charged to the job
  - Knowing the timing behavior of the run-time system we could incorporate overhead costs in schedulability tests

Real-time operating systems /1

- Tasks must be known to the RTOS
  - Tasks are the unit of CPU allocation by the scheduler
    - Tasks issue jobs, one at a time, which are subject to scheduling and dispatching
    - The scheduler decides which task gets the CPU
      - Typically by the position assigned to tasks in the ready queue
    - The dispatcher gets tasks to run and operates the context switch
- On task creation, some RAM is assigned to the ***Task Control Block*** for that task
  - The insertion of a task in a state queue (e.g., ready) is made by placing a pointer to the relevant TCB
  - The disposal of a task at end of life requires removal of its TCB and de-allocation of any memory it had in use
    - In typical embedded systems, tasks *never* terminate

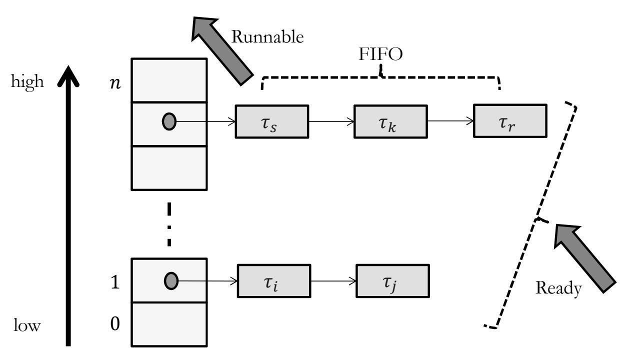
Task control block



Priority levels /1

- The scheduling techniques that we have studied assume jobs to have *distinct* priorities
  - It is not obvious however that concrete systems can always meet this requirement
  - Consequently jobs may have to share priority levels
  - At the same level of priority, dispatching may be FIFO or round-robin
- If priority levels are shared then we have a worst-case situation to contemplate in the analysis
  - That job J be released immediately *after* all other jobs residing at its level of priority

Priority levels /2



Priority levels /3

- Let $S(i)$ denote the set of jobs $J_{\{j\}}$ with $\pi_j = \pi_i$, excluding J_i itself
- The time demand equation for J_i to study in the interval $0 < t \le \min(D_i, p_i)$ then becomes
  - $\omega_{i_1}(t) = e_i + B_i + \sum_{S(i)} e_i + \sum_{k=1,..,i-1} \left\lceil \frac{\omega_{i_1}(t)}{p_k} \right\rceil e_k$
- This obviously worsens J_i's response time
  - But the impact in terms of ***schedulability loss*** at system level may not be as bad (see later …)

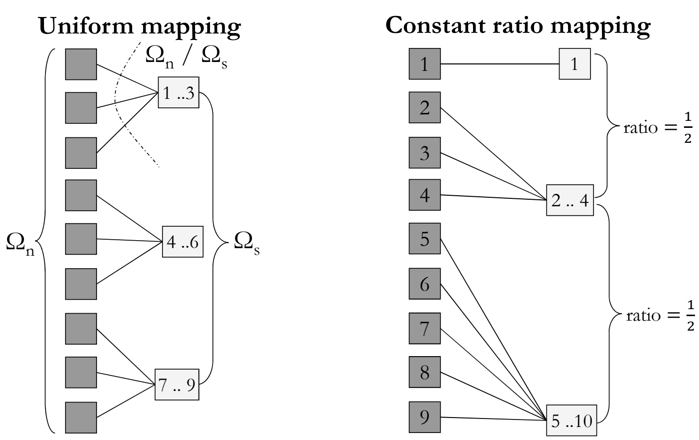
Priority levels /4

- When the number $[1,..,\Omega_n]$ of *assigned priorities* is greater than the number $[\pi_1,..,\pi_{\Omega_s}]$ of *available priorities* (a.k.a. **priority grid**) then we need some $\Omega_n{:}\,\Omega_s$ mapping
  - All (top-range) assigned priorities $\ge \pi_1$ take value π_1
  - For $1 < k \le \Omega_s$, the assigned priorities in the range $(\pi_{k-1}, \pi_k]$ take value π_k
- Two main techniques
  - **Uniform mapping**
  - **Constant ratio mapping** [Lehoczky & Sha, 1986]

Priority levels /5

- **Uniform mapping**
  - Uniformly apportions availability to demand
  - $Q = \left\lfloor \frac{\Omega_n}{\Omega_s} \right\rfloor \Rightarrow \pi_k = kQ, k = 1,2,..,\Omega_s - 1, \pi_{\Omega_s} = \Omega_n$
  - **Example**: with $\Omega_n = 9, \Omega_s = 3$ and $\pi_1 = 1, \pi_2 = 2, \pi_3 = 3$ we have $Q = 3$ hence $[1..3] \rightarrow \pi_1, [4..6] \rightarrow \pi_2, [7..9] \rightarrow \pi_3$
- **Constant ratio mapping**
  - Keeps the ratio $g = \frac{(\pi_{i-1}+1)}{\pi_i}$ constant for $i = 2,..,\Omega_s$ for the better good of higher-priority jobs
  - **Example (as above)**: with constant ratio $\frac{1}{2}$ and $\pi_1 = 1$ we have $\pi_2 = 4, \pi_3 = 10, \ldots$ so that $[1] \rightarrow \pi_1, [2..4] \rightarrow \pi_2, [5..9] \rightarrow \pi_3$

Priority levels /6



Priority levels /7

- Lehoczky & Sha showed that the use of constant ratio mapping degrades the schedulable utilization of RMS *gracefully*
  - For large n, with $D_i = p_i \; \forall i$, and $g = min_{2 \le j \le \Omega_s} \frac{(\pi_{j-1}+1)}{\pi_j}$, the schedulable utilization $f(g)$ evaluates to
    - $f(g) = ln(2g) + 1 - g$ for $g > \frac{1}{2}$
    - $f(g) = g$ for $g \le \frac{1}{2}$
- The $\frac{f(g)}{ln(2)}$ ratio is termed ***relative schedulability*** in relation to the RM schedulable utilization
  - **Example**: with Ω_s = 256 and Ω_n = 100,000 relative schedulability evaluates to 0.9986, which shows that 256 priority levels suffice for RMS

Real-time operating systems /2

- Must be small, modular, extensible
  - **Small footprint** because they are often stored in ROM (which used to be little) and because most embedded systems have little RAM anyway
    - Real-time embedded systems do not include permanent storage other than for background aperiodic activities
  - **Modular** because this facilitates verification, validation and certification of its design and implementation, including of temporal predictability
  - **Extensible** because some but not all specific systems may need functionalities above and beyond the core ones
- Adhering to the principle of microkernel architecture
  - Minimal kernel services include scheduling, inter-process communication and synchronization, interrupt handling

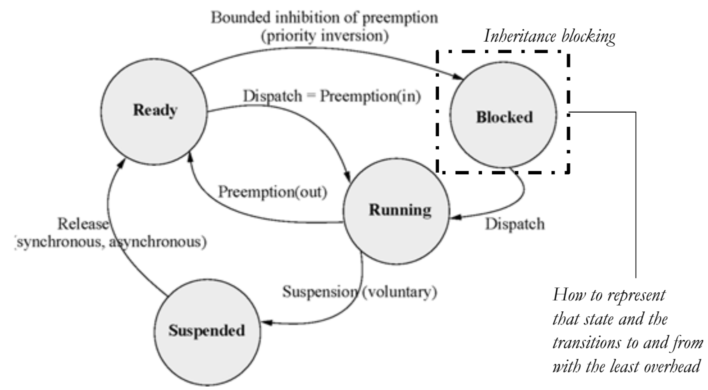
Real-time operating systems /3

- Tasks may be realized as specialized primitive entities living within the RTOS
  - In that case the model of concurrent computation is solely determined by the RTOS
- Or at application level with generic support from the RTOS API (e.g., pthread_*)
  - In that case it is up to the user to ensure care that the actual implementation corresponds with the analysis model if feasibility guarantees must be had

Real-time operating systems /4

- *Periodic task*
  - An RTOS thread that hangs on a periodic suspension point
    - After release it executes the application-code of the job and then calls into the suspension
- *Sporadic task*
  - An RTOS thread whose suspension point is not released periodically but with guaranteed minimum distance
    - After release it executes the job and then calls into the suspension
- *Aperiodic task*
  - Indistinguishable from the rest other than its being placed in a server's backlog queue and not in the ready queue

Task states /1



Task states /2

- Tasks enter the *suspended* state only voluntarily
  - By making a primitive invocation that causes them to hang on a periodic / sporadic suspension point
- The RTOS needs specialized structures to handle the distinct forms of suspension
  - A time-based queue for periodic suspensions
  - An event-based queue for sporadic suspensions
    - But someone shall still take care of warranting minimum separation between subsequent releases (!)

The scheduler /1

- This is a distinct part of the RTOS that does not execute in response to explicit application invocations
- It acts every time a task changes state (hence the ready queue does)
  - The corresponding time events are termed *dispatching points*
- Scheduler "activation" is often periodic in response to *clock interrupts*

The scheduler /2

- At every clock interrupt the scheduler must
  - Manage the queue of time-based events pending
  - Increment the execution time budget counter of the running job to support time-based scheduling policy (e.g., LLF)
  - Manage the ready queue
- The $\geq 10ms$ period (a.k.a. ***tick size***) typical of general-purpose operating systems is not fit for RTOS
  - But a higher frequency incurs larger overhead
- The scheduler needs to make provisions for event-driven execution too

Tick scheduling /1

- So far we have tacitly assumed that the scheduler operates on an *event-driven* basis
  - The scheduler always immediately executes upon the occurrence of a *scheduling event*
  - If it was so then we could reasonably assume that a job is placed in the ready queue at its release time
- Schedulers may also operate in a *time-driven* manner
  - In that case the scheduling decisions are made and executed on the arrival of periodic clock interrupts
  - This mode of operation is termed *tick scheduling*

Tick scheduling /2

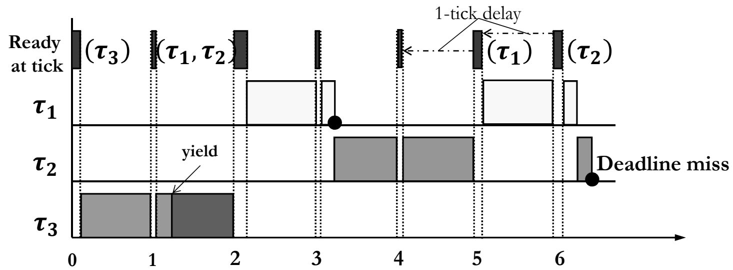
- The tick scheduler may acknowledge a job's release time 1 (scheduling) tick later than it arrived
  - This delay has negative impact on the job's response time
  - We also need to assume that a logical place exists where jobs in the "*release time arrived but not yet acknowledged*" state are held
  - The time and space overhead of transferring jobs from that logical place to the ready queue is not null and must be accounted for in the schedulability test together with the time and space overhead of handling clock interrupts

Example

$(\varphi_i, p_i, e_i, D_i)$

$T = \{\tau_1 = \{0.1, 4, 1, 4\}, \tau_2 = \{0.1, 5, 1.8, 5\}, \tau_3 = \{0, 20, 5, 20\}\}$
τ_3 with a first not preemptable section of duration 1.1

With RTA and event-driven scheduling $R_1 = 2.1, R_2 = 3.9, R_3 = 14.4$ (OK)
What with tick scheduling, clock period 1 and time overhead $0.05 + (0.06 \times n)$?



Tick scheduling /3

- The effect of tick scheduling is captured in the RTA for job J_i
  - By introducing a notional task $\tau_0 = (p_0, e_0)$ at the highest priority to account for the e_0 cost of handling periodic clock interrupts
  - For all jobs $J_k : \pi_k \geq \pi_i$, by adding to e_k the time overhead m_0 due to moving each of them to the ready queue
    - $(K_k + 1)$ times for the K_k times that job J_k may self suspend
  - For every individual jobs $J_l: \pi_l < \pi_i$, by introducing a distinct notional task $\tau_\gamma = (p_l, m_0)$ to account for the time overhead of moving them to the ready queue
  - Computing $B_i(np)$ as function of p_0: J_i may suffer up to p_0 units of delay after becoming ready even without non-preemptable execution
    - $B_i(np) = (\left\lceil max_k(\frac{\theta_k}{p_0})\right\rceil + 1)p_0$ before including non-preemption
    - Where θ_k is the maximum time of non-preemptable execution by any job J_k

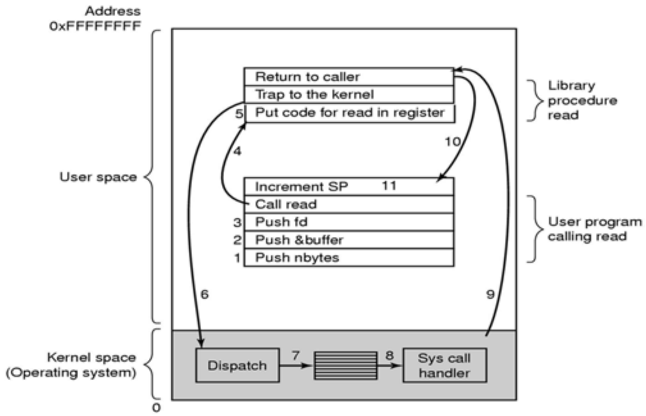
System calls /1

- The most part of RTOS services are executed in response to direct or indirect invocations by tasks
  - These invocations are termed *system calls*
- System calls need not be directly visible to the application
  - They are hidden in procedure calls exported by compiler libraries
  - The library procedure does all of the preparatory work needed to make the correct invocation of the actual system call on behalf of the application

System calls /2

- In embedded systems the RTOS and the application share memory
  - Not the case in general-purpose operating systems
  - Real-time embedded applications are more trustworthy and we do not want to pay the space and time overhead arising from address space separation
  - The RTOS must then protect its own data structures from the risk of race condition
- RTOS services must therefore be non-preemptable

System calls /3



I/O issues

- The I/O subsystem of a real-time system may require its own scheduler
- Simple methods to access an I/O resource
  - Use a run-to-completion non-preemptive FIFO policy
  - Use some kind of TDMA scheme
    - Non-preemptive quantized
- Priority-driven scheduling techniques as those in use for processor scheduling
  - RM, EDF, LLF can be used to schedule I/O requests

Interrupt handling /1

- HW interrupts are the most efficient manner for the processor to notify the application about the occurrence of external events
  - E.g., completion of asynchronous I/O operations like DMA (direct memory access)
- Frequency and computational load of the interrupt handling activities vary with the interrupt source

Interrupt handling /2

- For reasons of efficiency the interrupt handling service is typically subdivided in an *immediate* part and a *deferred* part
  - The immediate part executes at the level of interrupt priorities, above all SW priorities
  - The deferred part executes as a normal SW activity
- The RTOS must allow the application to tell which code to associate to either part
  - Interrupt service can also have a *device-independent* part and a *device-specific* part

Interrupt handling /3

- When the HW interface asserts an interrupt the processor saves state registers (e.g., PC, PSW) in the interrupt stack and jumps to the address of the needed *interrupt service routine* (ISR)
  - At this time interrupts are disabled to prevent race conditions on the arrival of further interrupts
  - Interrupts arriving at that time may be lost or kept pending (depending on the HW)
- Interrupts operate at an assigned level of priority so that interrupt service is subject to scheduling

Interrupt handling /4

- Depending on the HW the interrupt source is determined by *polling* or via an *interrupt vector*
  - Polling is HW independent hence more generally applicable but it increases latency of interrupt service
  - Vectoring needs specialized HW but it incurs less latency
- After the interrupt source has been determined registers are restored and interrupts are enabled again

Interrupt handling /5

- The worst-case latency incurred on interrupt handling is determined by the time needed to
  - Complete the current instruction, save registers, clear the pipeline, acquire the interrupt vector, activate the trap
  - Disable interrupts so that the ISR can be executed at the highest priority
    - This duration corresponds to *interference across interrupts*
  - Save the context of the interrupted task, identify the interrupt source and jump to the corresponding ISR
  - Begin execution of the selected ISR

Interrupt handling /6

- To reduce *distributed overhead*, the deferred part of the interrupt handling service must be preemptable
  - Hence it must execute at software priority
- But it still may directly or indirectly operate on RTOS data structures
  - Which must be protected by appropriate access control protocols
  - If we can do that then we do not need the RTOS to spawn its own tasks for this purpose

Interrupt handling /7

- To achieve better responsiveness for the deferred part of interrupt services schemes such as *slack stealing* or *bandwidth preservation* could be used
  - Bandwidth preservation retains the reserve of execution budget not used by aperiodic activities across periodic replenishments
- But their implementation needs specialized support from the RTOS

Time management /1

- A system clock consists of
  - A periodic counting register
    - Automatically reset to the *tick size* every time it reaches the *triggering edge* and triggers the *clock tick*
  - The register a *hardware part* automatically decremented at very clock pulse and a *software part* incremented by the handler of the clock tick
  - A queue of time events fired in the interval, whose treatment is pending
  - An (immediate) interrupt handling service

Time management /2

- The frequency of the clock tick fixes the *resolution* (granularity) of the *software part* of the clock
  - The resolution should be an integer divisor of the tick size so that the RTOS may perform tick scheduling at every N clock ticks
  - Then we have more frequent time-service interrupts and less frequent ($\frac{1}{N}$) clock interrupts
    - Time-service interrupts maintain the system clock
    - Clock interrupts are used for scheduling

Time management /3

- The software clock resolution is an important RTOS design parameter
  - The finer the resolution the better the clock accuracy but the larger the time-service interrupt overhead
- There is delicate balance between the clock accuracy needed by the application and the clock resolution that can be afforded by the system
  - Latency is intrinsic in any query made by a task to the software clock
    - E.g., 439 clock cycles in ORK for the Leon microprocessor
- The resolution cannot be finer-grained than the maximum latency incurred in accessing the clock (!)

Time management /4

- Beside periodic clocks RTOS may also support *one-shot timers* a.k.a. interval timers
  - They operate in a programmed (non-repetitive) way
- The RTOS scans the queue of the programmed time events to set the time of the next interrupt due from the interval timer
  - The resolution of the interval timer is limited by the time overhead of its handling by the RTOS
    - E.g., 7,061 clock cycles in ORK for Leon
      - www.dit.upm.es/~ork/

Time management /5

- The accuracy of time events is given by the difference between the time at which the event occurred and the time value as programmed
- It depends on three fundamental factors of influence
  - The frequency at which the time-event queues are inspected
    - If interval timers were not used, this would correspond to the period of time-service interrupts
  - The policy with which the RTOS handles the time-event queues
    - LIFO vs. FIFO
  - The time overhead cost of handling time events in the queue
- The release time of periodic tasks is inherently exposed to jitter (!)

Fine-grained response time analysis

R_i is a *compositional* term

Its RHS benefits from *composable* terms

$$R_i^{n+1} = B_i + CS1 + C_i + \sum_{j \in hp(i)} \left\lceil \frac{R_i^n + J_j^A}{T_j} \right\rceil (CS1 + C_j + TS + CS2) + I_{clock}^{R_i^n} + I_{extInt}^{R_i^n}$$

Blocking time (resource access protocol or *kernel*)

"In" context switch

"Activation" jitter

Time to issue a *suspension* call

"Out" context switch

Interference from the clock

Interference from interrupts

$$R_i^0 = B_i + CS1 + C_i$$

$$R_i = R_i^n + J^W$$

"Wake-up" jitter

Summary

- RTOS design issues
- Context switch
- Priority levels
- Tick scheduling
- Interrupt handling
- Time management

Selected readings

- T. Vardanega, J. Zamorano, J.A. de la Puente (**2005**)
  On the Dynamic Semantics and the Timing Behavior of Ravenscar Kernels
  DOI: 10.1023/B:TIME.0000048937.17571.2