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Priority Assignment in Fixed Priority Pre-emptive Systems with Varying Context Switch Costs

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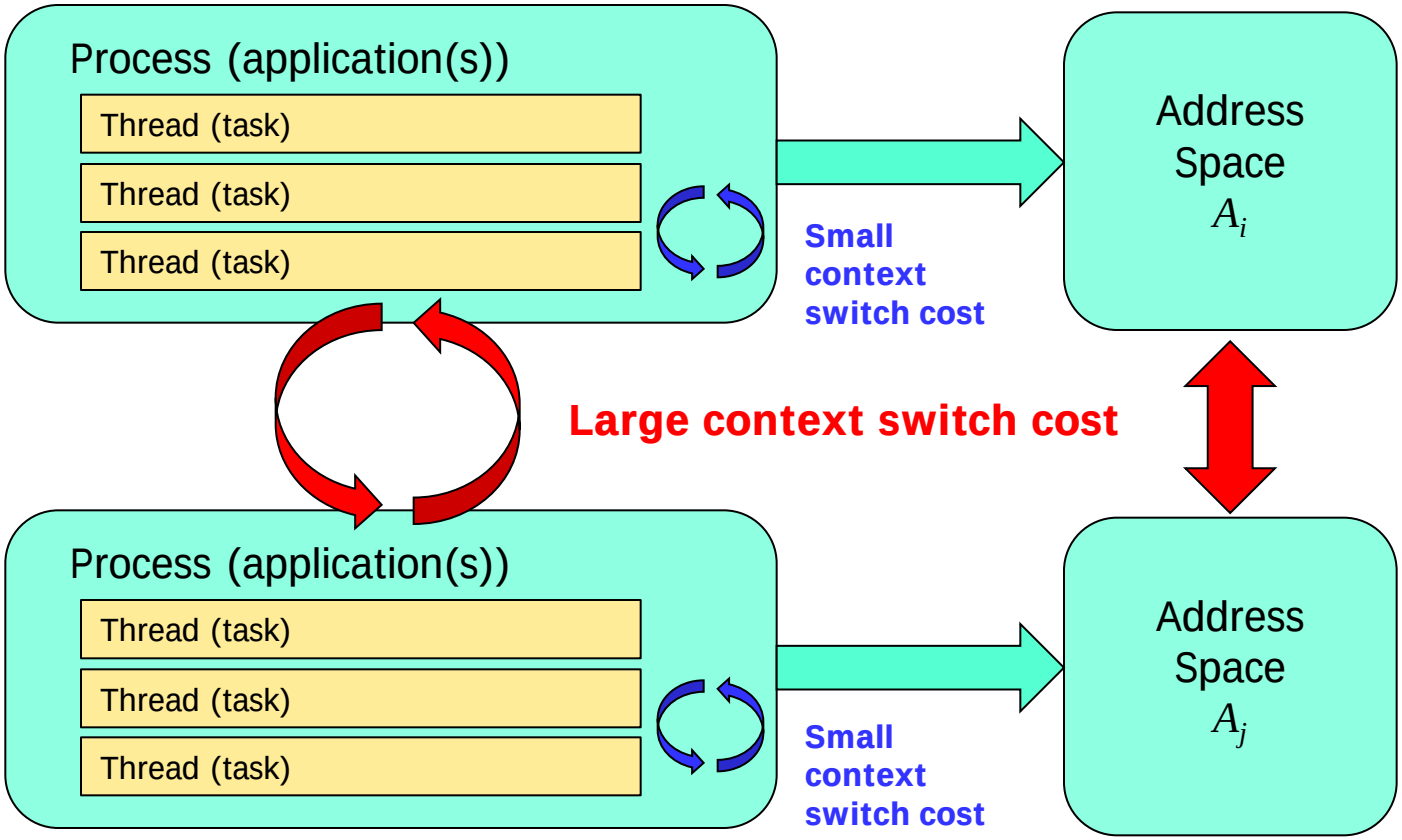
Motivation: Temporal and Spatial Separation

- Separation is vitally important
  - Safety standards (IEC61508, DO-178C, ISO26262) require that either all applications are developed to the standard required for the highest criticality application, or that independence between different applications is demonstrated in both spatial and temporal domains
- Process and Thread model
  - Each process has a separate memory address space
  - Threads within a process share the same address space
- Enables spatial and temporal separation
  - By mapping all tasks from a given application to a distinct process (one process per application)
  - Or by mapping all tasks of a given criticality level to a distinct process (one process per criticality level)

[R.I. Davis, S. Altmeyer, A. Burns, "Mixed Criticality Systems with Varying Context Switch Costs ". *In proceedings IEEE Real Time and Embedded Technology and Applications Symposium (RTAS 2018)* 11-13th Apr 2018]

Processes and Threads



Key point: Two very different context switch costs

System Model

- Single processor
- Fixed priority pre-emptive scheduling (FPPS)
- Sporadic tasks
  - Each task τ_i
  - T_i – Period or minimum inter-arrival time (sporadic behaviour)
  - D_i – Constrained relative deadline
  - C_i – worst-case execution time

- Additionally
  - Each task is mapped to an address space A_i (and process)
  - When one task τ_i pre-empts another task τ_j
    same address space ($A_i = A_j$) implies a small context switch cost C^S
    change in address space ($A_i \neq A_j$) implies a large context switch cost C^C
    (Here costs are for switching from and later back to the pre-empted task)

Response Time Analysis for FPPS: Simple Analysis

- Method
  - Use large context switch cost C^C for every pre-emption
  - Equivalent to subsuming context switch times into WCET bounds
  - Response time for task τ_i

$$R_i = C_i + C^C + \sum_{\forall j \in \mathrm{hp}(i)} \left\lceil \frac{R_i}{T_j} \right\rceil (C_j + C^C)$$

  - Fixed point iteration (converges or ends when value exceeds D_i)

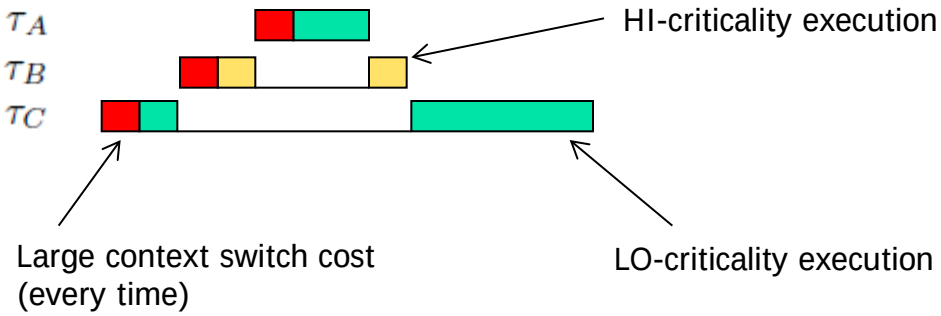
Response Time Analysis for FPPS: Simple Analysis

- Example:
  - Three tasks with parameters $(C_i, D_i, T_i, L_i, A_i)$

$$\tau_A = (10, 50, 100, LO, A^L)$$
$$\tau_B = (10, 100, 200, HI, A^H)$$
$$\tau_C = (200, 265, 300, LO, A^L)$$

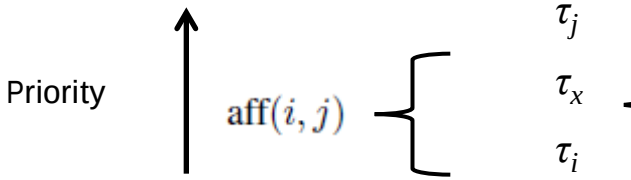
  - Further $C^C = 5$ and $C^S = 0$
  - Deadline Monotonic Priority Order (DMPO) is optimal
  - With priority order $\{A, B, C\}$ then $R_C = 280$ hence task set is not schedulable

  - Part of schedule illustrating context switch costs



Response Time Analysis for FPPS: Refined Analysis

- Method
  - Consider the set of tasks $\text{aff}(i,j) = \text{hep}(i) \cap \text{lp}(j)$ that can be *affected* by pre-emption by task τ_j during the response time of task τ_i



Lower priority than τ_j so they can be pre-empted by τ_j At least the priority of τ_i so they can run within its response time

  - Only get a large context switch cost for pre-emption by task τ_j if there is some task τ_h that can be pre-empted by task τ_j during the response time of task τ_i that belongs to a different process and hence different address space

$$\gamma_{i,j} = \begin{cases} C^C & \text{if } \exists h \in \text{aff}(i,j) | A_h \neq A_j \\ C^S & \text{otherwise} \end{cases}$$

$$R_i = C_i + C^C + \sum_{\forall j \in \text{hp}(i)} \left\lceil \frac{R_i}{T_j} \right\rceil (C_j + \gamma_{i,j})$$

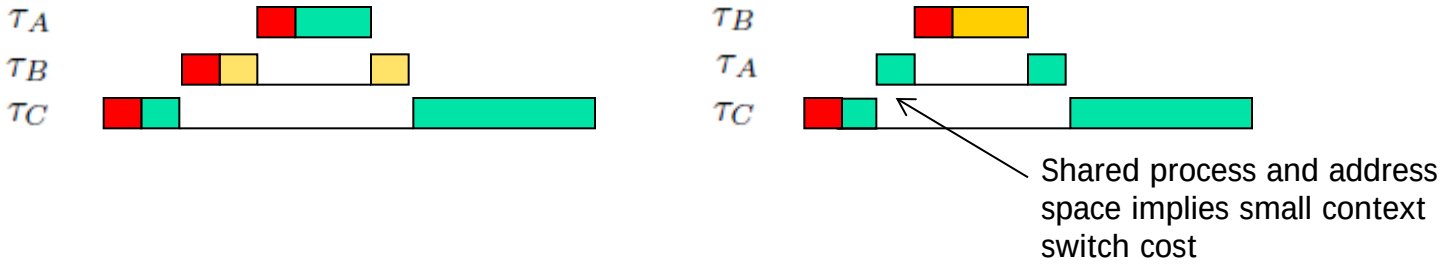
Response Time Analysis for FPPS: Refined Analysis

- Example:
  - Three tasks with parameters $(C_i, D_i, T_i, L_i, A_i)$

$$\tau_A = (10, 50, 100, LO, A^L)$$
$$\tau_B = (10, 100, 200, HI, A^H)$$
$$\tau_C = (200, 265, 300, LO, A^L)$$

  - Further $C^C = 5$ and $C^S = 0$
  - Deadline Monotonic Priority Order (DMPO) is **not** optimal
  - With priority order $\{A, B, C\}$ then $R_C = 280$ hence task set is not schedulable
  - With priority order $\{B, A, C\}$ then $R_C = 265$ and task set is schedulable

  - Part of schedule illustrating context switch costs



Response Time Analysis for FPPS: Multiset Analysis

- See the RTAS 2018 paper for details of the multiset analysis
  - Multiset analysis dominates the refined analysis

[R.I. Davis, S. Altmeyer, A. Burns, "Mixed Criticality Systems with Varying Context Switch Costs ". *In proceedings IEEE Real Time and Embedded Technology and Applications Symposium (RTAS 2018)* 11-13th Apr 2018]

Open Problem: Efficient Optimal Priority Assignment

- How to efficiently obtain an optimal priority assignment* with respect to the refined analysis? (and with respect to the multiset analysis?)

*An optimal priority assignment is one that is schedulable whenever there exists a schedulable priority assignment for the system

Audsley's algorithm: Optimal Priority Assignment (OPA)

```
for each priority level i, lowest first {
    for each unassigned task τ {
        if τ is schedulable at priority i
        assuming that all unassigned tasks are
        at higher priorities {
            assign task τ to priority level i
            break (exit for loop)
        }
    }
    if no tasks are schedulable at priority i {
        return unschedulable
    }
}
return schedulable
```

$n(n+1)/2$ schedulability tests rather than $n!$
by exhaustively exploring all possible orderings

(e.g. for n=15, 120 schedulability tests compared to 1307674368000)

OPA algorithm applic

Powerful idea as we have said very little about the actual schedulability test hence broad applicability

- OPA algorithm provides optimal priority ... schedulability test S for fixed priority schedu... that three conditions are met...

Condition 1: Schedulability of a task m..., accordin... to the test, be dependent on the set of higher p...rity ta...sk... but n...t on their relative priority ordering

Condition 2: Schedulabilit... of a task m..., accordin... to the test, be dependent on the s... of low... p...rity tasks ...ut not on their relative priority orderin...

Condition 3: When th... pri...ities of a... two tasks of adjacent priority are swap...d, the ...sk be... assign... the higher priority cannot become unsc...edu...b... a...co...ing to ...e test, if it was previously deemed sched...lab... ...t the low... priority

PROBLEM

[R.I. Davis and A. Burns "Improved Priority Assignment for Global Fixed Priority Pre-emptive Scheduling in Multiprocessor Real-Time Systems". *Real-Time Systems*, (2011) Volume 47, Number 1, pages 1-40]

Priority assignment toolbox: Techniques to explore #1

- Task swapping
  - Idea is to establish rules under which schedulability continues to hold when we swap two specific tasks in the priority order (This is the basis of many proofs of optimal priority orderings)
  - Can then use those rules to transform any schedulable ordering into another one with those tasks in a particular order without loss of schedulability
  - This might provide additional information / properties that hold for an optimal priority ordering which can then be used to reduce the complexity of finding it
- Hints and tips
  - If we swap two tasks from the same process under what circumstances would they both remain schedulable?

[R. I. Davis, L. Cucu-Grosjean, M. Bertogna, A. Burns, "A Review of Priority Assignment in Real-Time Systems". *Journal of Systems Architecture* (2016).]

Priority assignment toolbox: Techniques to explore #2

- Results from research into Robust Priority Assignment
  - Prior work on Robust Priority Assignment has shown that Deadline Monotonic is the optimal priority order for tasks subject to an additional interference function
  - Additional interference function is very general – only has to be monotonically non-decreasing with respect to lower priority levels and increasing intervals over which interference is considered

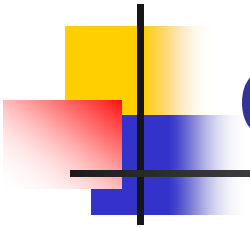
- Hints and tips
  - Perhaps it would be useful to consider a sub-set of tasks belonging to a specific process and regard all other tasks as just an additional interference function – we might then be able to show that Deadline Monotonic partial order is optimal for the sub-set of tasks in each process under the refined analysis?

[R.I. Davis, A. Burns. "Robust Priority Assignment for Fixed Priority Real-Time Systems". *In proceedings IEEE Real-Time Systems Symposium* pp. 3-14. Tucson, Arizona, USA. December 2007]

Priority assignment toolbox: Techniques to explore #3

- Sufficient test
  - If a task is schedulable at the lowest (unassigned) priority assuming a simple analysis (with all context switch costs assumed to be large) then it MUST be schedulable at that level with the refined and multiset analysis irrespective of the order of higher priority tasks
- Necessary test
  - If a task is unschedulable at the lowest (unassigned) priority assuming a simple analysis (with all context switch costs assumed to be small) then it CANNOT be schedulable at that level (with the set of higher priority tasks unchanged) under refined or multiset analysis irrespective of the order of higher priority tasks
- Hints and tips
  - Can these tests help us to build an optimal priority ordering for the refined analysis?

[R.I. Davis and A. Burns, "On Optimal Priority Assignment for Response Time Analysis of Global Fixed Priority Pre-emptive Scheduling in Multiprocessor Hard Real-Time Systems". University of York, Department of Computer Science Technical Report, YCS-2009-451, April 2010.]



Open Problems

- How to efficiently obtain an optimal priority assignment for the refined analysis? (and for the multiset analysis?)
  - For two processes?
  - For multiple processes?

- How best to schedule tasks when there are two different context switch costs (process-level and thread-level)?
  - Fully pre-emptive scheduling has the disadvantage of a large number of context switches
  - What about using non-preemptive scheduling or limited preemption scheduling?