Hard Real-Time Scheduling with Cache-Related Preemption Delays

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Seminar: http://labex-digicosme.fr/GT+OVSTR

Outline

Part I - Survey

- Background
  - Caching problems
  - Cache-related scheduling problem
- Cache-Related Scheduling Problems: State-of-The-Art
  - Main approaches
  - Classification and open issues

Part II - Several contributions

- CRPD-aware scheduling
  - Adding CRPD in the task model and analysis (optimality, sustainability, computational complexity)
  - Offline method and numerical results
- Cache-aware Scheduling
  - Adding cache state information in the task model
  - Computational complexity analysis

Context

Two major resources, that must be fully utilized

- computation: processors are fast
- memory: main memory is very slow and caches are very small

➢ Cache-Related Preemption Delays (CRPD) can represent up to 44% of the overall Worst-Case Execution Time (WCET) [1]–[4].

How to define efficient scheduling techniques for these resources...

- Where is the bottleneck (processors, caches, bus contention,...combination of them)?
- What is the impact of caches on scheduling problems?

Which Cache metrics for Real-Time Systems?

Hard Real-Time Systems

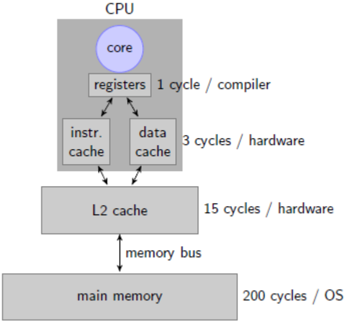
- CRPD bounds and Enhanced Schedulability Analysis (Jan Reineke's talk).
- Using CRPD and cache information to take scheduling decisions (this talk)

Soft-real Time Systems (not covered hereafter)

- Working Set Size: amount of cache lines accessed by a task (memory footprint)
- Stack Distance: number of different cache-lines accessed between two consecutive accesses to the same reference
- ...(see Hennessy and Patterson [5] for additional metrics)
- ...(see Calendrino and Anderson [6] for soft real-time syst.)

Caching Problems

- Current processors have cache memories



- Caches are resources with their own management unit (Replacement algorithm)
- cost(**cache miss**) $\gg$ cost(**cache hit**)
- Optimized for a single stream of sequential block requests

Cache replacement policy

Clairvoyant optimal algorithm [7]

(Belady's 1966 algorithm) Evict the block that will be used the furthest in the future

Online algorithms (competitive analysis [8])

➢ Adversary: optimal sequence for a size-k cache causes m misses.
➢ No (deterministic) on-line algorithm for a size-k cache can have a competitive ratio better than k (i.e., $k \times m$ cache evictions)

Basic observations

- Caches are mainly designed to reduce *intra*-task cache misses
- Periodic real-time tasks generate numerous *inter*-task misses (due to preemptions)

Cache-Related Preemption Delays (CRPD)

CRPD

Additional reloads because of cache evictions due to **preempting jobs**

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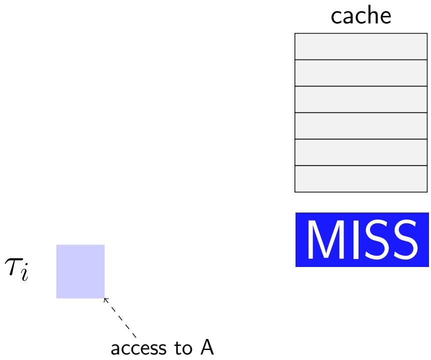

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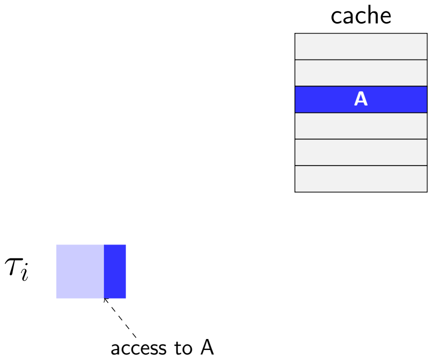

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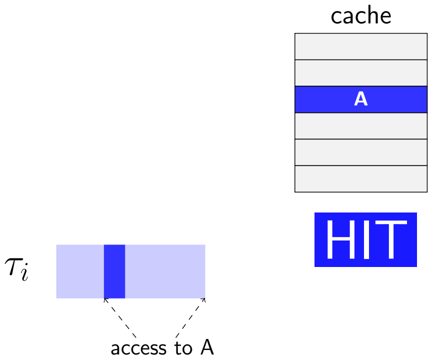

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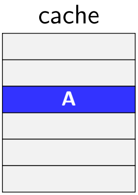

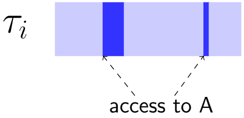

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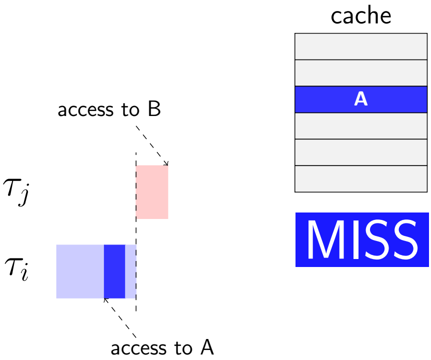

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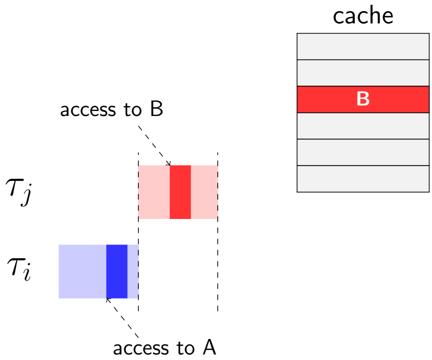

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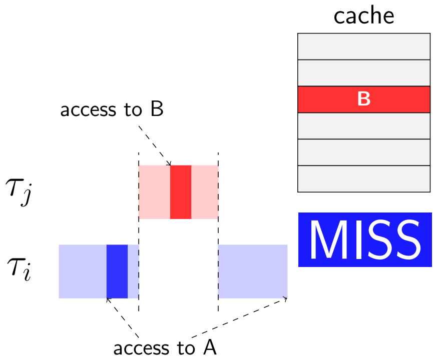

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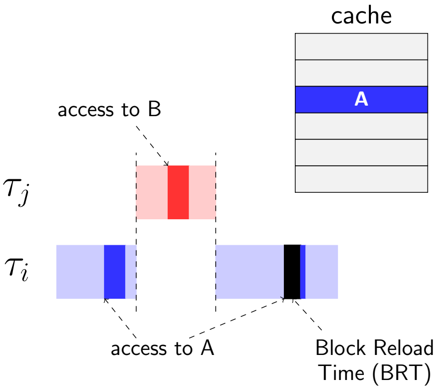

Cache-Related Preemption Delays (CRPD)

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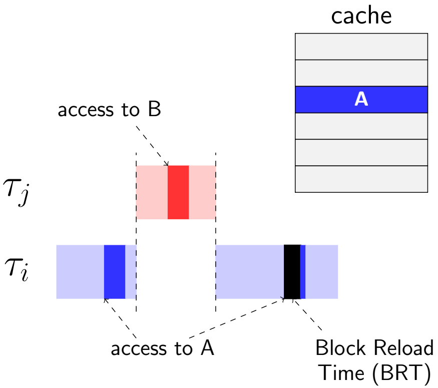
Additional reloads because of cache evictions due to **preempting jobs**

➢ ↗ System utilization (Up to 44% [1]–[4])



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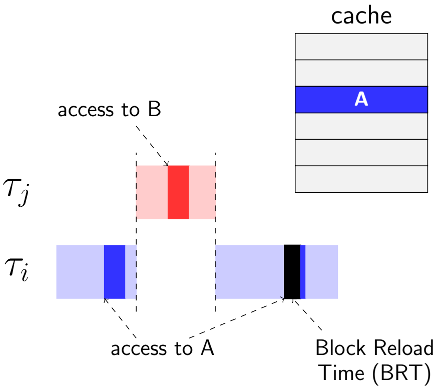

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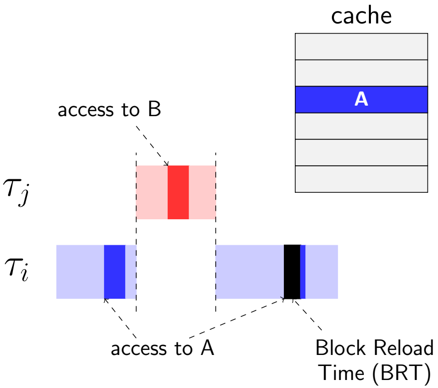


- ↗ System utilization (Up to 44% [1]–[4])
- predictability?
- schedulability?

Scheduling Theory: Basic Task models

Periodic (Sporadic) task

- Every task τ_i releases an infinite set of **jobs** $(\tau_{ij}, j = 1..\infty)$
- Every job as the same WCET C_i
- jobs are periodically released every T_i units of time (minimum interarrival time in the sporadic case)
- jobs are subjected to a deadline D_i units of time after their releases.

Deadlines

- Implicit: $D_i = T_i$
- Constrained: $D_i \leq T_i$
- Arbitrary: otherwise.

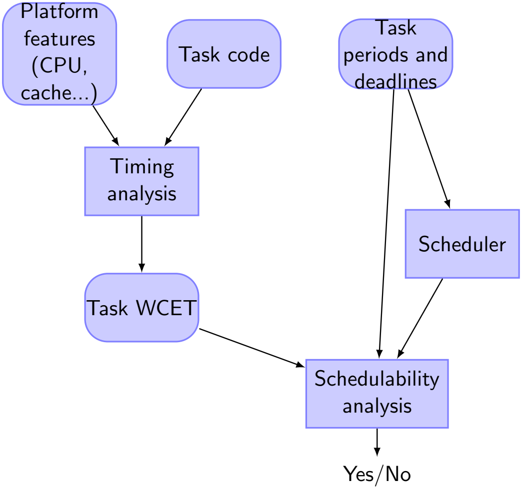
Outline

State-of-the-art (Tentative)

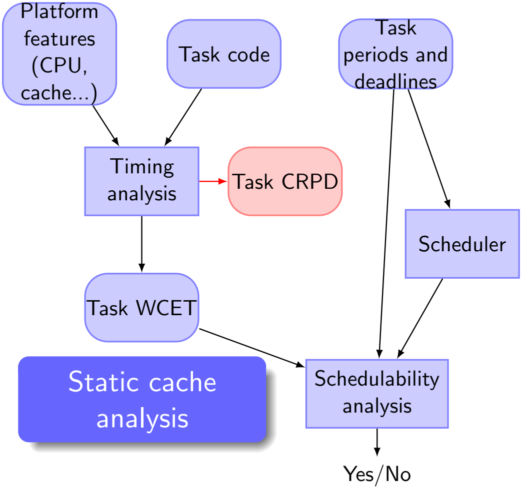
Main Approaches [9]

- Bounding CRPD and introducing it in schedulability tests
  ➢ WCET community
- Cache management: partitioning/locking cache lines
  ➢ Platform community
- Controlling preemptions points: static and dynamic approaches
  ➢ Scheduling Community

Bounding the CRPD



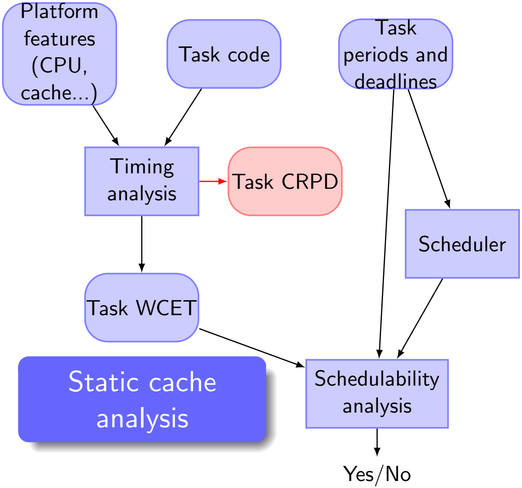
Bounding the CRPD



- preempted task
  ↪ Useful Cache Blocks (UCBs)

- *Lee et al. (1997, [10])*

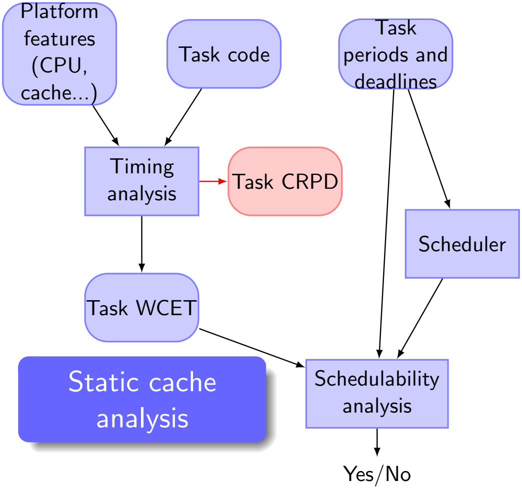
Bounding the CRPD



- preempted task
  - ↪ Useful Cache Blocks (UCBs)
- preempting task
  - ↪ Evicting Cache Blocks (ECBs)

- *Busquets-Mataix et al.(1996, [11])*

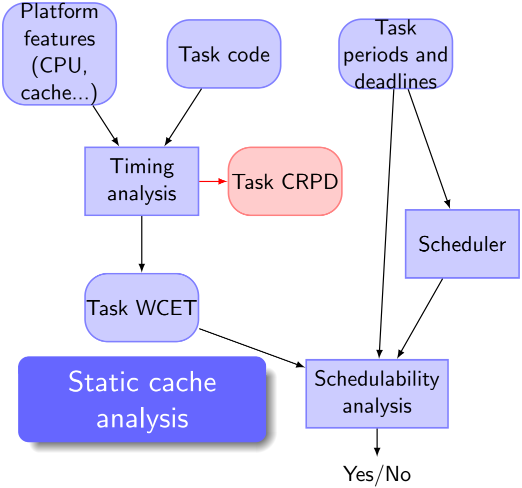
Bounding the CRPD



- preempted task
  - ↪ Useful Cache Blocks (UCBs)
- preempting task
  - ↪ Evicting Cache Blocks (ECBs)
- combined approaches
  - ↪ both tasks

- *Altmeyer et al. (2012, [12])*

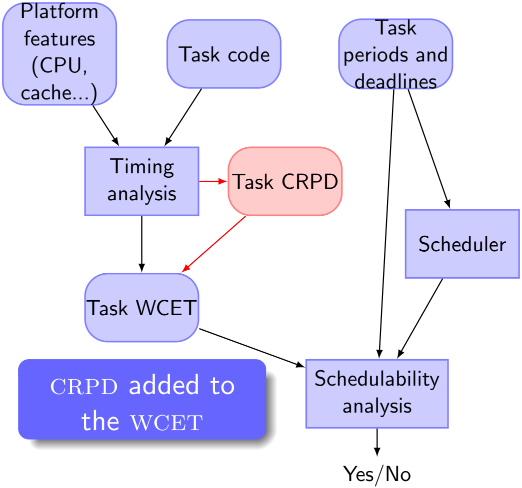
Bounding the CRPD



- preempted task
  - ↪ Useful Cache Blocks (UCBs)
- preempting task
  - ↪ Evicting Cache Blocks (ECBs)
- combined approaches
  - ↪ both tasks
- improvements:
  - ↪ Definitely-Cached UCBs

- *Altmeyer et al.(2009, [13])*

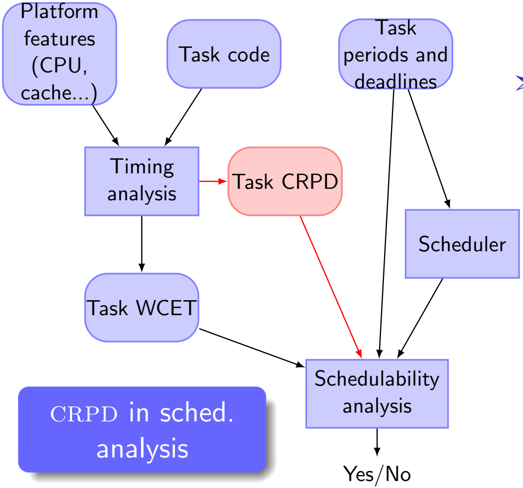
Bounding the CRPD



- $\text{WCET}_{\text{w/o preemption}} + n \times \text{CRPD}$
  - $\hookrightarrow n$?

- *Altmeyer et al.(2011, [14])*

Bounding the CRPD

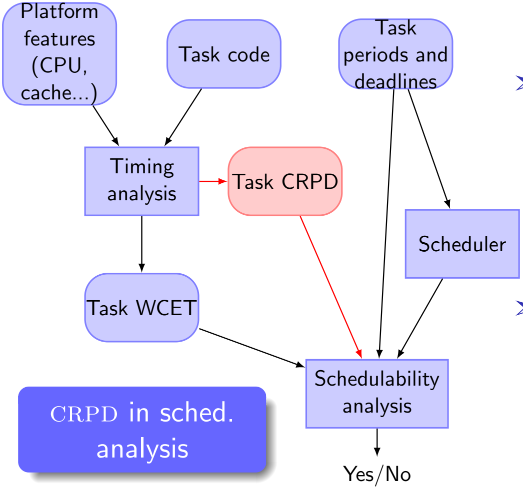


CRPD in sched. analysis

- Fixed-Priority (FP):
  $\hookrightarrow$ $R_i = C_i + \sum \left\lceil \frac{R_i}{T_j} \right\rceil \cdot (C_j + \gamma_{i,j})$

- *Busquets-Mataix et al.(1996, [11])*

Bounding the CRPD

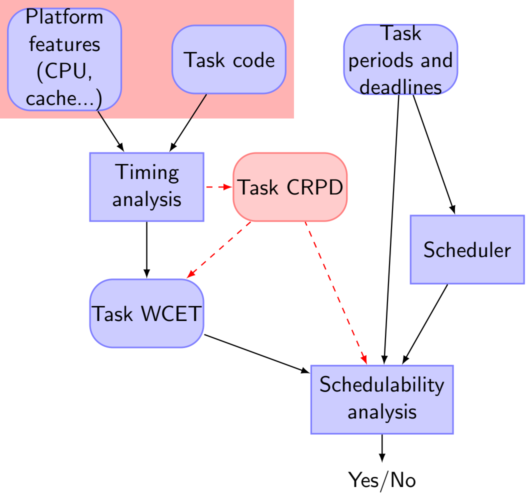


- Fixed-Priority (FP):
  - ↪ $R_i = C_i + \sum \left\lceil \frac{R_i}{T_j} \right\rceil \cdot (C_j + \gamma_{i,j})$
- EDF scheduling:
  - ↪ Similar to Fixed-Priority

CRPD in sched. analysis

- *Lunniss et al., (2013,[15])*

Cache management



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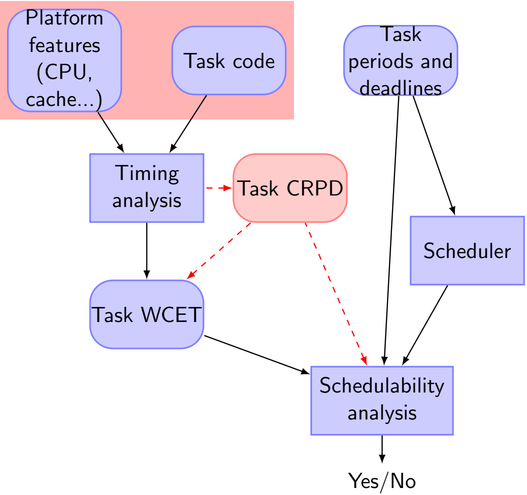
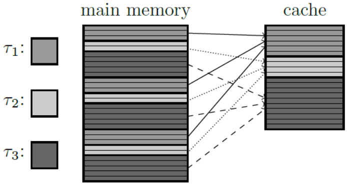
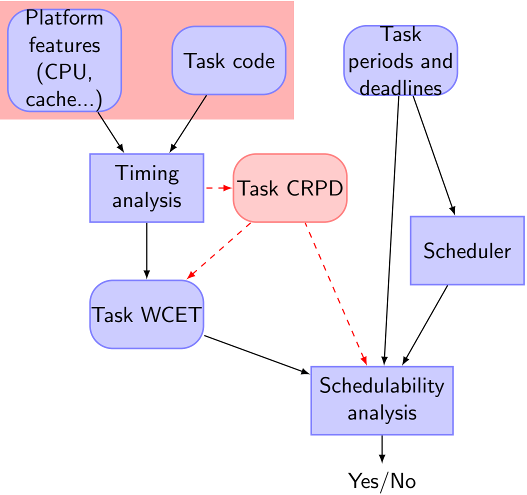


- cache partitioning



- *Bui et al. (2008,[16])*

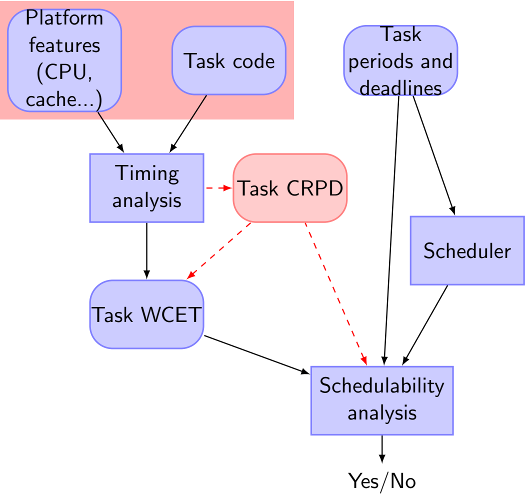
Cache management



- cache partitioning
- cache locking
  - → cache content fixed
    - ⇒ predictability

- *Ding et al. (2013,[17])*

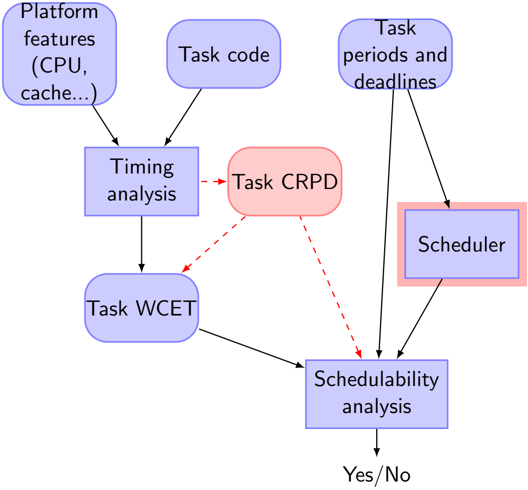
Cache management



- cache partitioning
- cache locking
  - → cache content fixed
    - ⇒ predictability
- memory layout
  - code positioning
    - ⇒ ↘ WCET
  - task positioning
    - ⇒ ↘ CRPD

- *Lunniss et al (2012,[18])*

Scheduling (Controlling preemptions)



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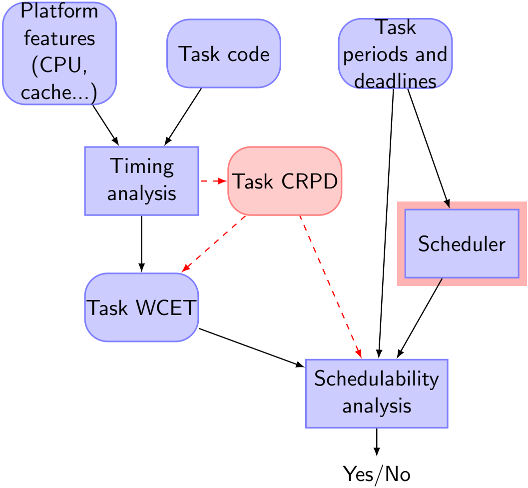
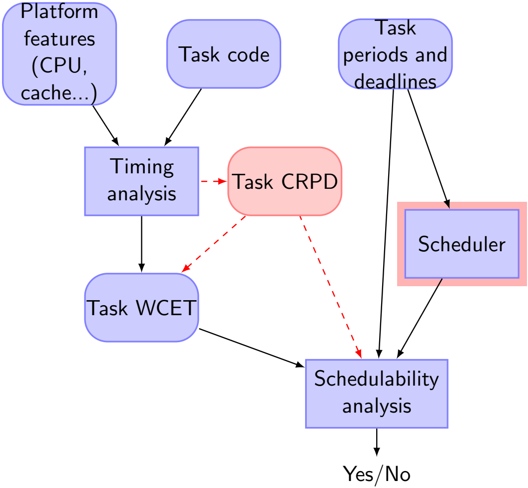


- Preemption Thresholds
  - ↪ preemption possible only if: priority(preempting task) > threshold(preempted task)

- *Bril et al. (2014,[19])*

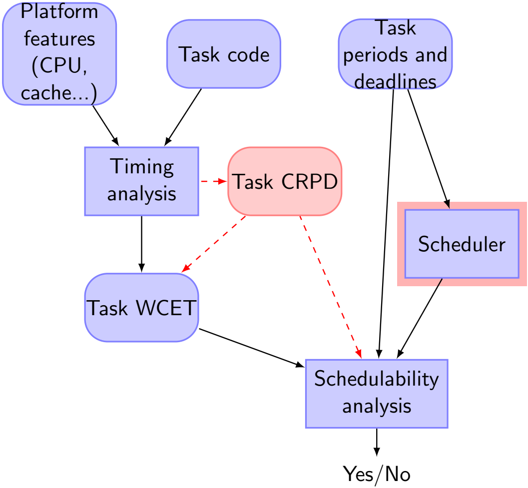
Scheduling (Controlling preemptions)



- Preemption Thresholds
  - ↪ preemption possible only if: priority(preempting task) > threshold(preempted task)
- Deferred Preemptions
  - ↪ preemption postponed as much as possible

- *Bertogna et al. (2010,[20])*

Scheduling (Controlling preemptions)



- Preemption Thresholds
  - ↪ preemption possible only if: priority(preempting task) > threshold(preempted task)
- Deferred Preemptions
  - ↪ preemption postponed as much as possible
- Fixed Preemptive Points
  - ↪ Offline Stage: preemptions allowed only at precomputed program points, to minimize CRPD;
  - ↪ Online stage: standard online priority scheduling.

- *Bertogna et al. (2011,[21])*

State-of-the-art (Tentative)

category	techniques		references
Memory Management	cache partitioning	fully-partitioning	[22]–[25]
		hybrid-partitioning	[16], [26]
	cache locking	full locking	[27]–[33]
		partial locking	[17], [34]
	partitioning + locking		[35]
	memory layout		[18], [36]–[42]
WCET	WCET integrating cache analysis		[43]–[48]
	CRPD in WCET	preempting task	[49], [50]
		preempted task	[13], [14], [51]
		both tasks	[52]–[54]

State-of-the-art (Tentative (Cont'))

category	techniques			references
Sched.	CRPD in Sched. Analysis	Preempting task		[11], [55]
		Preempted task		[56]
		both tasks		[12], [15], [57], [58]
	Preemption Control	Floating Non Preemptive Region	CRPD as a function	[59], [60]
		Preemption Thresholds	Opt+CRPD in Sched. Analysis	[19], [61]

State-of-the-art (Tentative (Cont'))

category	techniques			references
Sched. (Cont')	Preemption Control (Cont')	Deferred Preemption	opt.+ CRPD in Sched. Analysis	[4], [21], [62]–[65]

State-of-the-art scheduling techniques

- Integrating CRPD into existing scheduling techniques (i.e., FP, EDF, and their variants are considered).
- Results mainly for direct-mapped caches

Open issues (from scheduling point of view)

Approved!!

Timing and Schedulability Analysis must take into account CRPD.

Which granularity of the task model for improving scheduling decisions?

- fine-grained: exploiting cache state information?
- coarse-grained: worst-case CRPD as the maximum preemption delay for a task set, for a task, for a segment within a task,...?

Scheduling algorithms

- Extend and mix known techniques?
- Need of new approaches?

Current Work in Poitiers (Guillaume's PhD Thesis)

Cache impact on *optimally* taking **scheduling decisions**

- Objective: define the most basic task models to cover:
  - ↪ the largest set of scheduling problems
  - ↪ all cache architectures (direct-mapped, Set-Associative and Full-Associative)
  - scheduling with *cache-related preemption delays*
    - → **crpd-aware scheduling problem**
  - scheduling with *cache state information*
    - → **Cache-aware scheduling problem**

Current collaborations

- Claire Maiza (Verimag, Grenoble)
- Joël Goossens (ULB, Brussels)

Outline

CRPD scheduling problem statement

Scheduling decisions exploit cache-related preemption delays
→ **minimize the total overhead** (i.e., sum of CRPDs).

Task model: $\tau_i(C_i, D_i, T_i, \gamma)$

- C_i: WCET without CRPD
  ↪ τ_i executed fully non preemptively
- γ: worst-case CRPD for one preemption
  ↪ the same for all program points and all tasks

Presented results [66], [67]

- Optimality and Complexity Analyses
- Sustainability Analysis (scheduling anomalies)
- Competitive Analysis (i.e., online v.s. offline schedulers)
- Optimal offline scheduling method and numerical results

Optimality Analysis

Example ($\tau_i(C_i, D_i, T_i, \gamma)$): $\tau_1(1, 3, 3, 0.6)$, $\tau_2(7, 12, 12, 0.6)$

Optimality Analysis

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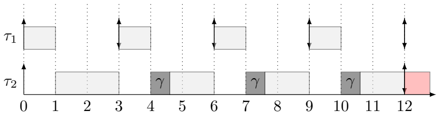
- Fixed-Task/Fixed-Job Priority Scheduling:



$\rightarrow$ not schedulable

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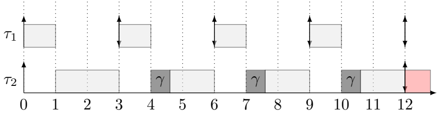

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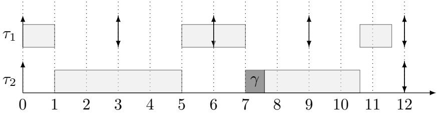
- CRPD-aware scheduling:



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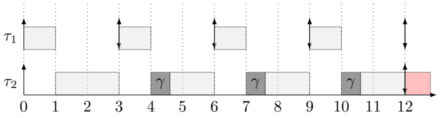

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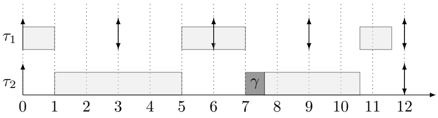

$\rightarrow$ schedulable

$\Rightarrow$ Fixed-Task and Fixed-Job Priority schedulers $\rightarrow$ **not optimal**.

Optimality Analysis (Cont')

Finite set of synchronous tasks $\tau_i(C_i, D_i, T_i, \gamma)$,

$\hookrightarrow$ Is there a uniprocessor preemptive schedule meeting the deadlines?

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$\hookrightarrow$ Is there a uniprocessor preemptive schedule meeting the deadlines?

$\Rightarrow$ **NP-hard** in the *strong sense*.

Proof [67]: transformation from the 3-Partition decision problem

Optimality Analysis (Cont')

Proof (Sketch)

3-Partition [68]

- Instance: a set A of $3m$ elements, a bound $B \in N$, and a size $s_j \in N$ for each $j = 1..3m$ such that $B/4 < s_j < B/2$ and $\sum_{j=1..3m} s_j = mB$.
- Question: Can A be partitioned into m disjoint sets $A_1, A_2, ..., A_m$ such that, for $1 \leq i \leq m$, $\sum_{j \in A_i} s_j = B$ (each A_i must therefore contain exactly three elements from A)?

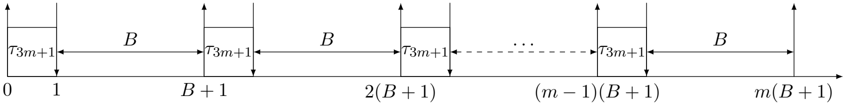
Transformation: To every 3-Partition instance

- $3m$ tasks $\tau_1, \ldots, \tau_{3m}$ with the parameters: $C_i = s_i, D_i = T_i = m(B+1)$, $1 \leq i \leq 3m$.
- Task τ_{3m+1} with: $C_{3m+1} = D_{3m+1} = 1$ and $T_i = (B+1)$

Optimality Analysis (Cont')

Proof sketch (Cont') In the task set defined from a 3-Partition instance:

- the workload is 100% without preemption
- In every feasible schedule, the pattern follows:



Property

A schedule is feasible if, and only if, there is no preemption (one preemption leads to a workload $> 100\%$).

Optimality Analysis (Cont')

- Set of jobs with 2 distinct releases and deadlines and $\gamma = 1$

$\Rightarrow$ NP-hard in the *weak sense*.

Proof [69]: transformation from the 2-Partition decision problem

Optimality Analysis (Cont')

- Set of jobs with 2 distinct releases and deadlines and $\gamma = 1$

$\Rightarrow$ NP-hard in the *weak sense*.

Proof [69]: transformation from the 2-Partition decision problem

- EDF still optimal for finite set of jobs with either:
  - $r_i = 0$
  - $d_i = d$
  - $C_i = 1$
  - similarly ordered release times and deadlines: $r_i \leq r_j \Rightarrow d_i \leq d_j$

$\rightarrow$ since no job is preempted using EDF

Sustainability analysis

Sustainability definition

A scheduling policy is sustainable if any systems deemed schedulable remain schedulable if:

- a WCET is decreased
- a period is increased
- a relative deadline is increased

NEW preemption delay is decreased

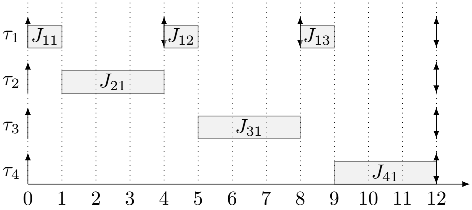
Known results for uniprocessor without CRPD [70]

- EDF is sustainable with respect to: WCET, period, deadlines
- Fixed-Task Priority (RM,DM) is sustainable w.r.t.: WCET, deadlines

EDF, RM and DM non Sustainability w.r.t. WCET

➢ 4 tasks ($\tau_i(C_i, D_i, T_i, \gamma)$): $\tau_1(1, 4, 4, 0.6)$, $\tau_2(3, 12, 12, 0.6)$, $\tau_3(3, 12, 12, 0.6)$ and $\tau_4(3, 12, 12, 0.6)$

➢ EDF, RM and DM use the same job priority assignment (task index as tie breaker).



→ schedule with $C_2 = 3$

EDF, RM and DM non Sustainability w.r.t. WCET

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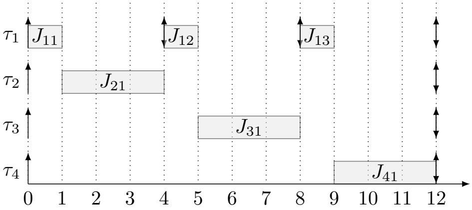
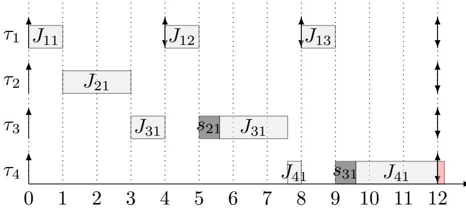


→ schedule with $C_2 = 3$

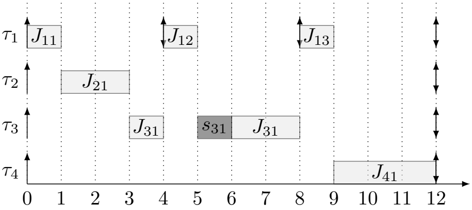


→ schedule with $C_2 = 2$

EDF, RM and DM non Sustainability w.r.t. Preemption delays

➢ 4 tasks ($\tau_i(C_i, D_i, T_i, \gamma)$): $\tau_1(1,4,4,1)$, $\tau_2(3,12,12,1)$, $\tau_3(3,12,12,1)$ and $\tau_4(3,12,12,1)$

➢ EDF, RM and DM use the same job priority assignment (task index as tie breaker).

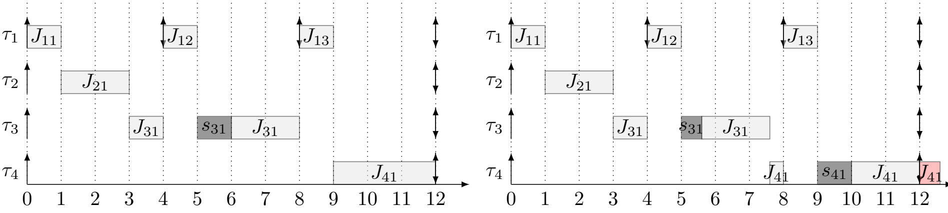


$\rightarrow$ schedule with $\gamma = 1$

EDF, RM and DM non Sustainability w.r.t. Preemption delays

➢ 4 tasks ($\tau_i(C_i, D_i, T_i, \gamma)$): $\tau_1(1, 4, 4, 1)$, $\tau_2(3, 12, 12, 1)$, $\tau_3(3, 12, 12, 1)$ and $\tau_4(3, 12, 12, 1)$

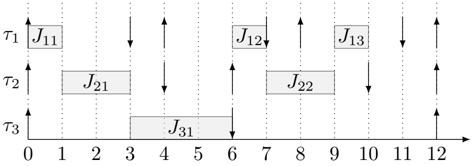
➢ EDF, RM and DM use the same job priority assignment (task index as tie breaker).



→ schedule with $\gamma = 1$ → schedule with $\gamma_{31} \leq 1$

EDF non Sustainability w.r.t. relative deadlines

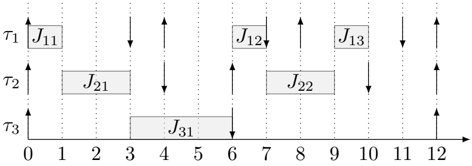
- 3 tasks ($\tau_i(C_i, D_i, T_i, \gamma)$): $\tau_1(1,3,4,1)$, $\tau_2(2,4,6,1)$, $\tau_3(3,6,12,1)$
- EDF (task index as tie breaker).



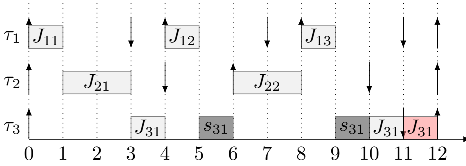
$\rightarrow$ EDF schedule with $D_3 = 6$

EDF non Sustainability w.r.t. relative deadlines

- 3 tasks ($\tau_i(C_i, D_i, T_i, \gamma)$): $\tau_1(1, 3, 4, 1)$, $\tau_2(2, 4, 6, 1)$, $\tau_3(3, 6, 12, 1)$
- EDF (task index as tie breaker).



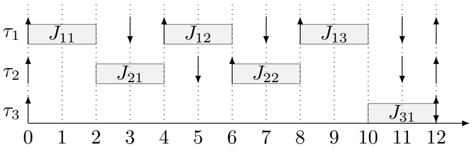
$\rightarrow$ EDF schedule with $D_3 = 6$



$\rightarrow$ EDF schedule with $D_3 = 11$

EDF non Sustainability w.r.t. periods

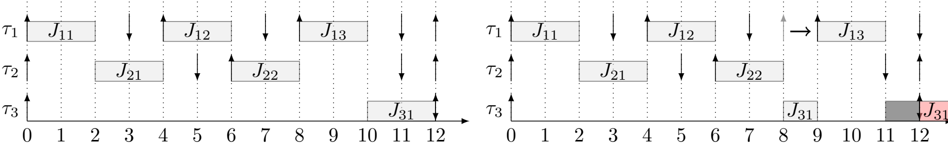
- 3 tasks ($\tau_i(C_i, D_i, T_i, \gamma)$): $\tau_1(2,3,4,1)$, $\tau_2(2,5,6,1)$, $\tau_3(2,12,12,1)$
- Shifting one release time (sporadic tasks)



$\rightarrow$ EDF schedule with $T_1 = 4$

EDF non Sustainability w.r.t. periods

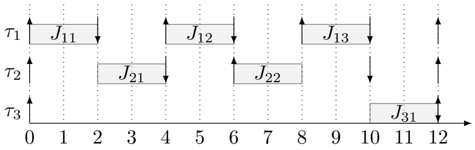
- 3 tasks ($\tau_i(C_i, D_i, T_i, \gamma)$): $\tau_1(2,3,4,1)$, $\tau_2(2,5,6,1)$, $\tau_3(2,12,12,1)$
- Shifting one release time (sporadic tasks)



$\rightarrow$ EDF schedule with $T_1 = 4$ $\rightarrow$ EDF schedule with $T_1 = 5$

EDF non Sustainability w.r.t. periods

- 3 tasks ($\tau_i(C_i, D_i, T_i, \gamma)$): $\tau_1(2,3,4,1)$, $\tau_2(2,5,6,1)$, $\tau_3(2,12,12,1)$
- periodic tasks



$\rightarrow$ EDF schedule with $T_2 = 6$

EDF non Sustainability w.r.t. periods

- 3 tasks ($\tau_i(C_i, D_i, T_i, \gamma)$): $\tau_1(2, 3, 4, 1)$, $\tau_2(2, 5, 6, 1)$, $\tau_3(2, 12, 12, 1)$
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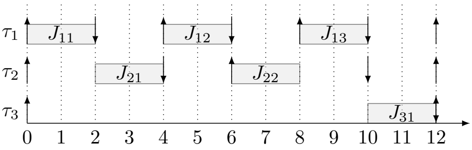
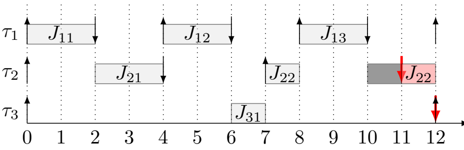


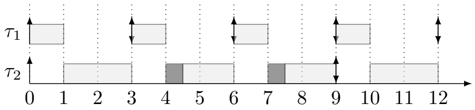
$\rightarrow$ EDF schedule with $T_2 = 6$



$\rightarrow$ EDF schedule with $T_2 = 7$

FP and critical instant worst-case scenario

- 2 tasks ($\tau_i(C_i, D_i, T_i, \gamma)$): $\tau_1(1, 3, 3, 0.5)$, $\tau_2(5, 9, 9, 0.5)$
- sporadic tasks scheduled by RM
- Similar examples in [47], [71]



$\rightarrow$ wcrt(τ_2)=9

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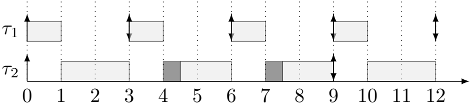
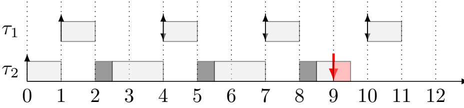




$\rightarrow$ wcrt(τ_2)=9

$\rightarrow$ wcrt(τ_2)=9.5

Competitive analysis

Online scheduling model

- Set of jobs released over time
- at each job release, all its parameters are known

Result: Optimal online scheduling is impossible

Job release times need to be a priori known to define an optimal online scheduler (i.e., clairvoyant).

Competitive analysis (Cont')

Proof sketch

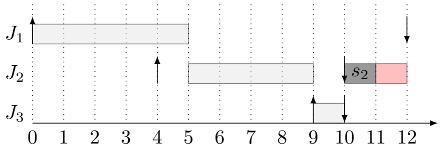
Optimal offline scheduler (the adversary) generates jobs so that any online scheduler cannot define a feasible schedule whereas the adversary can.

Adversary strategy:

1. Generate two jobs J_1(0,5,12,1) and J_2(4,5,6,1)
2. At time 4
   - Case 1 the online scheduler continues to execute τ_1
   - Case 2 the online scheduler preempts τ_1 to execute τ_2
3. According to the case, the adversary defines a new job τ_3.

Proof sketch (Cont')

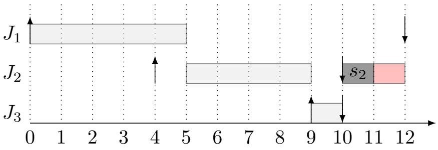
Case 1. The online scheduler continues to execute Job τ_1 at time 4. Adversary generates a job J_3(9,1,1,1).



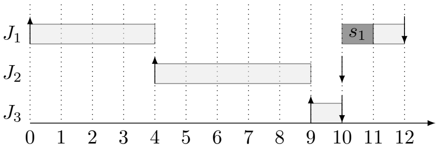
$\rightarrow$ Online algorithm

Proof sketch (Cont')

Case 1. The online scheduler continues to execute Job τ_1 at time 4. Adversary generates a job J_3(9,1,1,1).



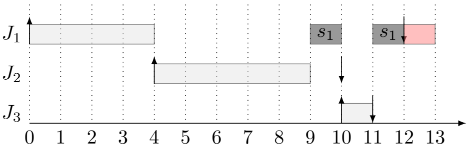
→ Online algorithm



→ Adversary's feasible schedule

Proof sketch (Cont')

Case 2. the online scheduler preempts τ_1 to execute τ_3 at time 4 τ_2. Adversary generates a job J_3(10,1,1,1).



→ Online algorithm

Proof sketch (Cont')

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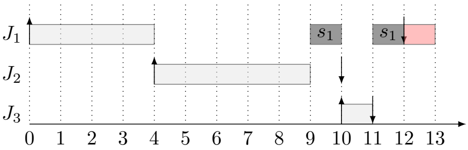
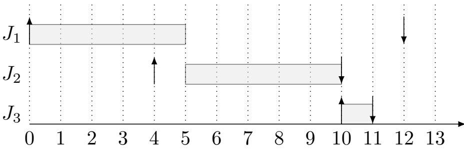




$\rightarrow$ Online algorithm

$\rightarrow$ Adversary's feasible schedule

Offline scheduling: MILP formulation

Mixed Integer Linear Program (MILP)

Define an offline schedule to:

- Minimize the total workload
- or equivalently, minimize the total preemption delay (since WCET contributes as a constant in the objective function)

Contraints:

- each job is executed for its WCET
- each job is executed between its release time and its deadline
- at most one job is executed at any time instant
- explicit preemption delay

MILP: schedule construction

Schedule Construction

- The schedule is defined as a finite set of slices S_j, separated by release dates/deadlines (No job release inside a slice).
- In every slice, job-pieces and their related preemption delays must fit in the slice interval

Main property to define a feasible schedule

Every job is executed at most once in every slice with no pmtn.

MILP Variables to define the schedule in each slice S_j

- $t_{i,j} \in \mathbb{R}$: starting time of job-piece τ_i in S_j
- $p_{ij} \in \mathbb{R}$: execution time of job-piece τ_i in S_j
- $\Delta_{ij} \in \{0, 1\}$: job-piece τ_i has to pay a pmtn. delay in S_j.

MILP: schedule construction (Cont')

Rewriting simplification

- Execution time modification: $C_i' = C_i - s_i$ (i.e., the first job-piece pays a fictive pmtn delay at release)
- Simpler formulation of pmtn. penalty constraints in the MILP

Simple example with two periodic tasks

Five jobs $J_i(r_i, C_i, s_i, D_i)$ generated within [0,12)

- Task 1: $J_1(0, 1, 0.2, 3)$, $J_2(3, 2, 1, 0.2, 3)$, $J_3(6, 1, 0.2, 3)$, $J_4(9, 1, 0.2, 3)$
- Task 2: $J_5(0, 7, 0.5, 12)$

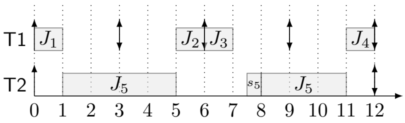
It can be easily checked that EDF generates 3 pmtn and misses a deadline.

MILP: schedule construction (Cont')

- 4 Slices: S_1=[0, 3),S_2=[3,6),S_3=[6,9),S_4=[9,12)
- 8 job-pieces (rows in the following table)

MILP results:

job-pieces		Variables			pmtn
job	slice	t_{ij}	C'_{ij}	Δ_{ij}	s_i
J_1	1	0	0.8	1	0.2
J_5	1	1	1.5	1	0.5
J_5	2	3	2	0	0.2
J_2	2	5	0.8	1	0.2
J_3	3	6	0.8	1	0.2
J_5	3	7.5	1	1	0.5
J_5	4	9	2	0	0.5
J_4	4	11	0.8	1	0.2



→ Optimal schedule

Experiments

Synthetic task sets

- (C_i, T_i) UUnifast to generate utilization factors
- s_i randomly generated between 0 and the Maximum Pmtn Delay Factor (PDF, percentage of the WCET C_i)
- Limited to 200 jobs over the hyperperiod (to limit CPLEX running time)

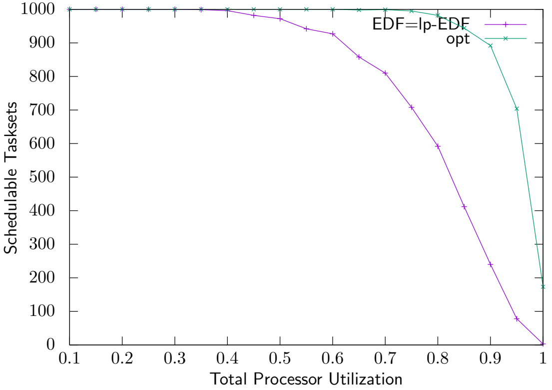
Monitored Algorithms

- EDF based algorithms
  - EDF: arbitrary tie breaker
  - LP-EDF: tie breaker avoid unnecessary preemptions
  - Cache-related schedulability analysis (Lunniss *et al.* RTAS'2013 [15])
- OPT: MILP solved by CPLEX 12.6.1

Results: Total Utilization

Experiment parameters

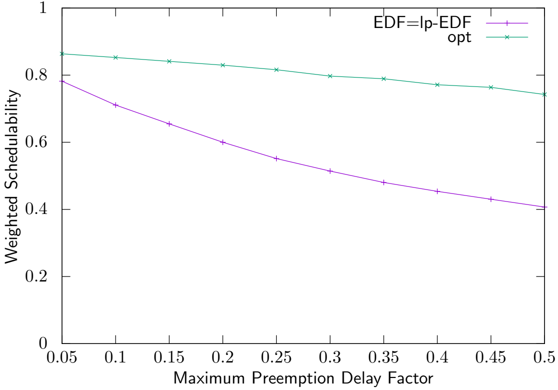
Maximum Preemption Delay Factor (PDF) 20%.



Results: Weighted Schedulability

Experiment parameters

Weighted Schedulability as a function of the Maximum PDF.



$Q = \{u | u = k \cdot 0.1, k \in [\![1, 10]\!]\}$

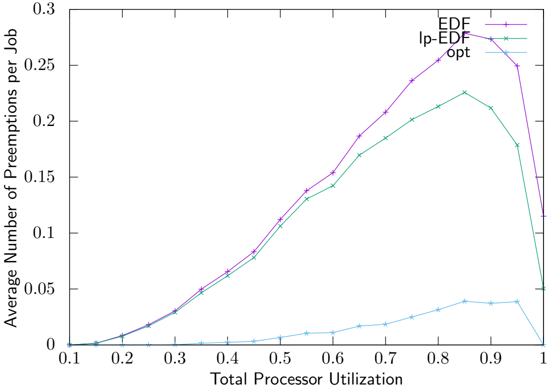
$$W_\ell(PDF) = \frac{\sum_{\forall U \in Q} U \cdot S_\ell(U, PDF)}{\sum_{\forall U \in Q} U}$$

with $S_\ell(U, PDF)$ binary sched. result

Results: Number of preemptions

Experiment parameters

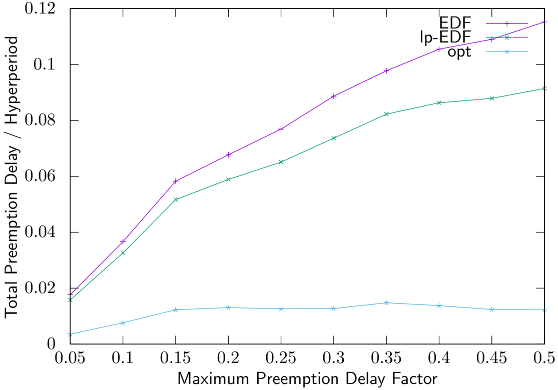
Average number of preemptions per job as function of U (PDF=20%).



Results: Total preemption delays

Experiment parameters

Total preemption delays as a function of maximum PDF.



Outline

Cache-aware scheduling problem

Scheduling with cache state information

Cache assumptions

- consists in a single cache line,
- miss cost $= BRT$ (Block Reload Time), hit=0
- block references: string of letters

Simple Job model

synchronous Job i: $J_i(C_i, D, S_i)$:

- C_i: WCET *without cache miss*,
- D: a common relative deadline for all jobs
- S_i: sequence of memory blocks used during the job execution
  - $\hookrightarrow$ One memory block used per time unit
  - $\hookrightarrow$ no *if-then-else* structure

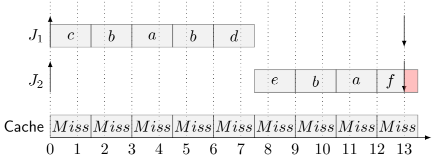
Example: $J_1(5, 13, cbabd)$, $J_2(4, 13, ebaf)$, BRT $= 0.5$

$$S_1 = c \to b \to a \to b \to d, \qquad S_2 = e \to b \to a \to f$$

Example: $J_1(5, 13, cbabd)$, $J_2(4, 13, ebaf)$, BRT $= 0.5$

$$S_1 = c \rightarrow b \rightarrow a \rightarrow b \rightarrow d, \quad S_2 = e \rightarrow b \rightarrow a \rightarrow f$$

- Fixed-Job Priority Scheduling ($prio(J_1) > prio(J_2)$):



$\rightarrow$ not schedulable

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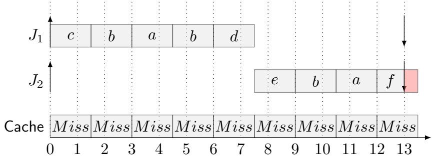
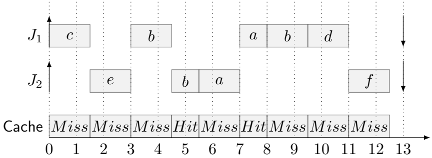


$\to$ not schedulable

- Cache-aware scheduling:



$\to$ schedulable

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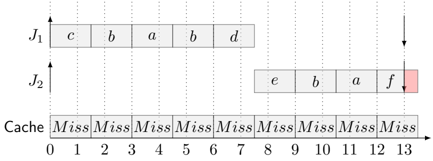

$\to$ not schedulable

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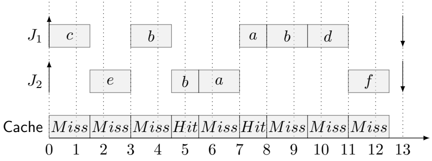

$\to$ schedulable

$\Rightarrow$ Fixed-Task and Fixed-Job Priority schedulers $\to$ **not optimal**.

Complexity result

Finite set of n jobs $J_i(C_i, D, S_i)$ with a common deadline D

$\hookrightarrow$ a uniprocessor preemptive schedule meeting the overall deadline D for every job J_i?

Complexity result

Finite set of n jobs $J_i(C_i, D, S_i)$ with a common deadline D

$\hookrightarrow$ a uniprocessor preemptive schedule meeting the overall deadline D for every job J_i?

$\Rightarrow$ **NP-hard** in the *strong sense*.

Proof (see [67]): Transformation from the Shortest Common Supersequence problem known to be strongly NP-Complete [68]

Outline

Conclusion

- **Real-Time Scheduling** with **Cache-Related Pmtn Delays**
- CRPD-*aware* scheduling problem
  - ↪ Scheduling anomalies for standard scheduling policies (i.e., FP,EDF)
  - ↪ **NP-hard** in the strong sense
    - ⇒ no pseudo-polynomial optimal scheduling algorithm
  - ↪ No optimal online scheduling policies (set of jobs)
- *Cache-aware* scheduling problem
  - ↪ RM, EDF are not optimal
  - ↪ **NP-hard** in the strong sense
    - ⇒ no pseudo-polynomial optimal scheduling algorithm

Perspectives

Continue to study basic task models

- to understand underlying theoretical problems
- to evaluate the performance of a given technique
- to delimit practical solutions for real-world problems

Scheduling under cache constraints

- Uniprocessor: evaluate the loss of schedulability of online schedulers
- Multiprocessors: timing issues are quite tricky

Perspectives (*Cont.*)

Circular dependencies must be taken into account

- Timing issues: CRPD computation under constraints (cache partitioning, Code positioning, enforced scheduling isolation,...)
- Compilers: code/task positioning to avoid bottlenecks in caches
- Cache management: partitioning/locking techniques
- Schedulers: taking into account all previously mentioned constraints

Models and Metrics

- Shared task models to fully exploit them at design stages (timing, scheduling analysis, scheduler)
- Common metrics to measure the relative contributions of mixed techniques

Thank you!
Questions?

References

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