Design and Analysis of Real-Time Systems

Bounding the Cache-Related Preemption Delay

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Outline

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1 Why Preemptive Scheduling?

2 CRPD Computation
- Analysis of the Preempted Task
- Analysis of the Preempting Task
- Analysis of the Preempted and the Preempting Task
- Simplifying or Eliminating the Problem
- Policies other than LRU

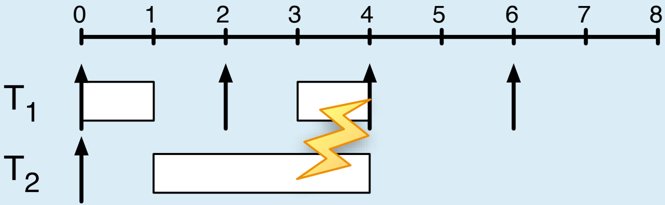
3 Summary

Why use preemptive scheduling?

- Preemption often increases schedulability of task sets.
- Tasks with short deadlines are often unschedulable non-preemptively.

Example

Given: Two periodic tasks T_1 and T_2, with periods $P_1 = 2, P_2 = 8$, deadlines $D_1 = P_1, D_2 = P_2$, and execution times $C_1 = 1, C_2 = 3$.



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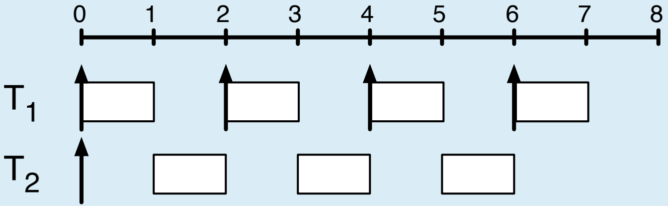
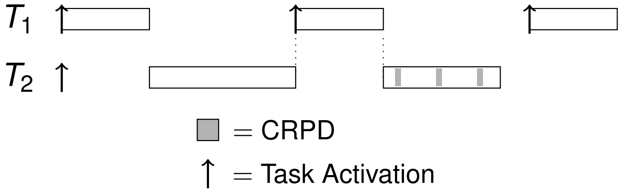


Preemption does not come for free!

- The preempting task "disturbs" the state of performance-enhancing features like caches and pipelines.
- Once the preempted task resumes its execution, the disturbance may cause additional *cache misses*.
- The additional execution time due to additional cache misses is known as the *cache-related preemption delay*.



How to take preemption cost into account?

Where to account for preemption cost?

- Integrate into WCET Analysis: [Schneider, 2000]
  - Assume cache misses everywhere
  - Very pessimistic but easy to use with existing schedulability analyses
- WCET Analysis + CRPD Analysis: [Lee et al., 1996]
  - $WCET_{bound} + n \cdot CRPD_{bound} \geq$ execution time of task with up to n preemptions
  - More precise but requires new schedulability analyses: except for some recent work by Davis, Altmeyer, and Maiza.

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Focus of this lecture: approaches to bound the CRPD
Out-of-scope: using these bounds within schedulability analyses

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CRPD Analyses

- Preempted Task:
  How many additional cache misses can a single preemption by *any* preempting task cause in a *given* preempted task?
- Preempting Task:
  How many additional cache misses can a single preemption by a *given* preempting task cause in *any* preempted task?
- Preempted + Preempting Task
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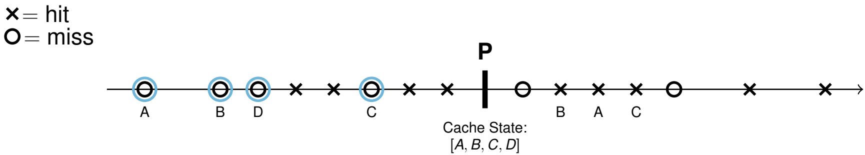
Analysis of the Preempted Task: Useful Cache Blocks (UCB)

Definition (Useful Cache Block, [Lee et al., 1996])

A memory block m at program point P is called a useful cache block, if

a) m may be cached at P

b) m may be reused at program point Q that may be reached from P with no eviction of m on this path.



$$\text{UCB} \supseteq \{A, B, C, D\}$$

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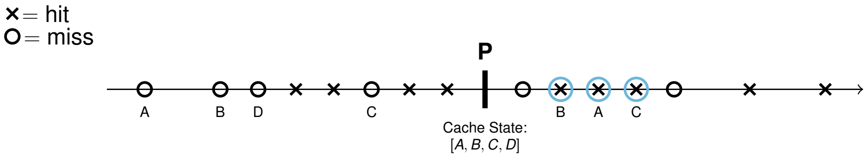
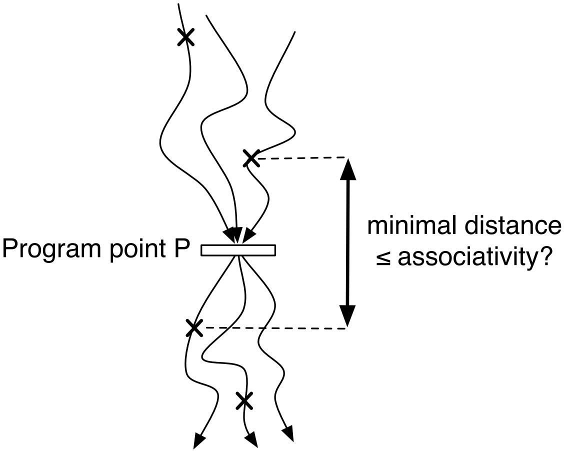


$$\text{UCB} = \{A, B, C\}$$

UCB Analysis



UCB Analysis

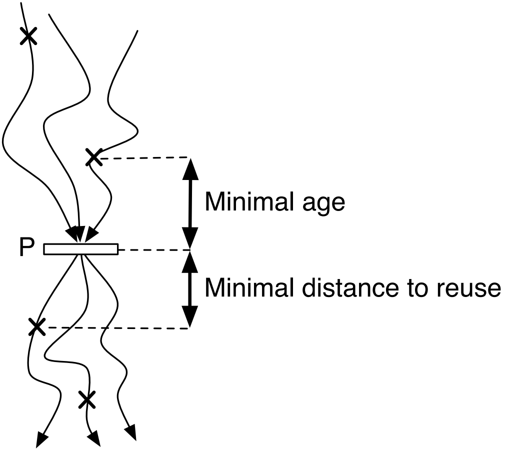
Combination of two LRU-may-analyses:

What may be cached?

Forward May-Analysis!

What may be reused?

Backward May-Analysis!

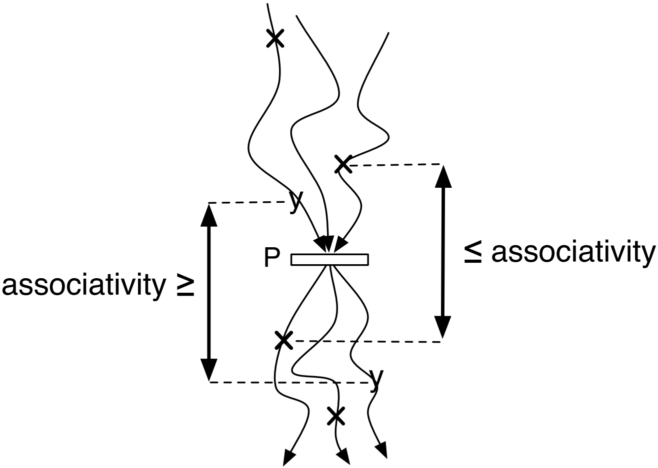


Minimal age + Minimal distance to reuse $\leq$ associativity

$\Longrightarrow$ Memory block may be useful

Improvement: Path Analysis

Some blocks are never useful at the same time:



Literature:
[Tomiyama and Dutt, 2000, Negi et al., 2003, Staschulat and Ernst, 2007]

Improvement:
Avoid Accumulating Overestimations

Schedulability analyses rely on:

$$\underbrace{WCET_{bound} + n}_{\text{\# of possible preemptions}} \cdot \underbrace{CRPD_{bound}}_{BRT \cdot |UCB|} \geq \text{exec. time with up to } n \text{ preemptions}$$

Yet, we usually have:

$$\begin{aligned} WCET_{bound} &\geq \text{execution time without preemptions} \\ CRPD_{bound} &\geq \text{additional execution time due to one preemption} \end{aligned}$$

$\Longrightarrow$ Overestimation in both analyses adds up:

Some cache misses are counted twice!

Bounding the CRPD using UCBs for Fully-Associative Caches

- CRPD bound at program point P:

$$\mathrm{CRPD}^{\mathrm{LRU}}_{\mathrm{UCB}}(P) = \mathrm{BRT} \cdot min(|\mathrm{UCB}(P)|, k),$$

where k = associativity and BRT = Block Reload Time

- CRPD bound independent of program point:

$$\mathrm{CRPD}^{\mathrm{LRU}}_{\mathrm{UCB}} = \max_{P} \mathrm{CRPD}^{\mathrm{LRU}}_{\mathrm{UCB}}(P)$$

Slightly more complicated for set-associative caches:
sum up bounds of all cache sets.

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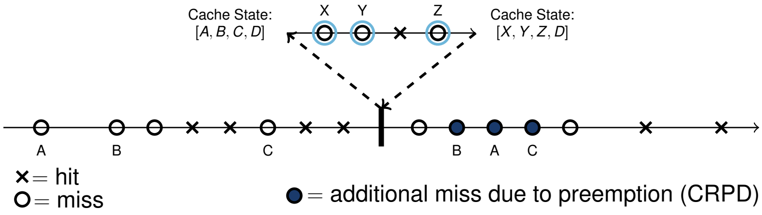
Analysis of the Preempting Task: Evicting Cache Blocks

Definition (Evicting Cache Blocks (ECB), [Tomiyama and Dutt, 2000])

A memory block of the preempting task is called an *evicting cache block*, if it may be accessed during the execution of the preempting task.



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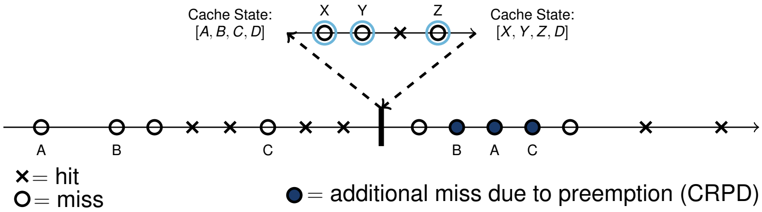
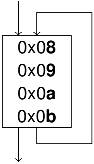


$$\mathrm{CRPD}_{\mathrm{ECB}}^{\mathrm{LRU}} \stackrel{?}{=} \mathrm{BRT} \cdot min(|\mathrm{ECB}|, k)$$

k = associativity

BRT = Block Reload Time

CRPD Computation for LRU using ECBs: Pitfall



$[b, a, 9, 8] \xrightarrow{8} [8, b, a, 9] \xrightarrow{9} [9, 8, b, a] \xrightarrow{a} [a, 9, 8, b] \xrightarrow{b} [b, a, 9, 8]$ 0 misses

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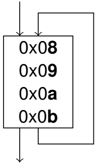

ECBs $= \{\mathbf{e}\}$

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$$[\mathbf{e}, b, a, 9] \xrightarrow{8^*} [8, \mathbf{e}, b, a] \xrightarrow{9^*} [9, 8, \mathbf{e}, b] \xrightarrow{a^*} [a, 9, 8, \mathbf{e}] \xrightarrow{b^*} [b, a, 9, 8] \quad \text{4 misses}$$

- $|\text{UCB}| = 4$
- $|\text{ECB}| = 1$
- $k =$ associativity $= 4$
- number of additional misses $= 4$

CRPD Computation for LRU using ECB: Sound but Imprecise

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- ECB analysis only to determine whether the set is used at all by the preempting task or not:

$$\mathrm{CRPD}^{\mathrm{LRU}}_{\mathrm{ECB}} = \begin{cases} 0 & \text{if ECB} = \emptyset \\ \mathrm{BRT} \cdot k & \text{otherwise} \end{cases}$$

- Cannot do better than that without knowledge of preempted task.

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Analysis of Preempted and Preempting Task: "Shallow" Combination

Take the minimum of the *UCB*- and *ECB*-based estimations.

- CRPD bound for entire program:

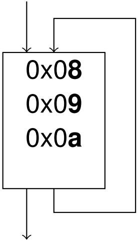
$$\text{CRPD}^{\text{LRU}}_{\text{UCB+ECB}} = \min(\text{CRPD}^{\text{LRU}}_{\text{ECB}}, \text{CRPD}^{\text{LRU}}_{\text{UCB}})$$

Becomes slightly more complicated for set-associative caches:
For a program point: sum of point-wise minima of all cache sets.

Literature:

- For direct-mapped caches: [Negi et al., 2003]
- For set-associative caches:
  [Tan and Mooney, 2004, Burguière et al., 2009]

Analysis of Preempted and Preempting Task: "Deeper" Combination



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Without preemption:

$$[a, 9, 8, 7] \xrightarrow{8} [8, a, 9, 7] \xrightarrow{9} [9, 8, a, 7] \xrightarrow{a} [a, 9, 8, 7]$$

With preemption:

$$[\mathbf{e}, a, 9, 8] \xrightarrow{8} [8, \mathbf{e}, b, a] \xrightarrow{9} [9, 8, \mathbf{e}, b] \xrightarrow{a} [a, 9, 8, \mathbf{e}]$$

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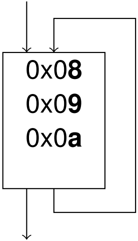

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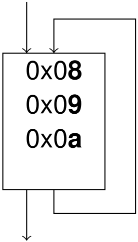

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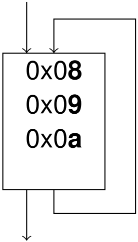

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Why?

- Minimal number of ECBs to evict a UCB is 2, but $|\text{ECB}| = 1$
- A single ECB is not sufficient to evict any of the UCBs.

Combining UCB and ECB: Notion of Resilience

Determining the maximal number of ECBs, such that no additional cache miss may occur:

$m \in UCB$

m

a_1 $[m, -, -, -, -, -, -, -]$

a_2

a_3 $[a_3, a_2, a_1, m, -, -, -, -]$

m $[m, a_3, a_2, a_1, -, -, -, -]$

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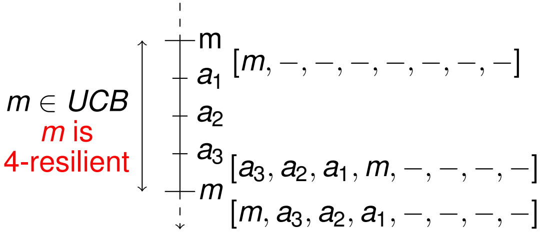

Resilience Analysis

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Definition (Resilience)

A memory block m is called *l-resilient* at program point P,
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- No UCB is k-resilient, i.e., no UCB remains useful after a preemption with k (= associativity) many ECBs.
- Each $(l+1)$-resilient UCB is also l-resilient.
- Each UCB is at least 0-resilient.

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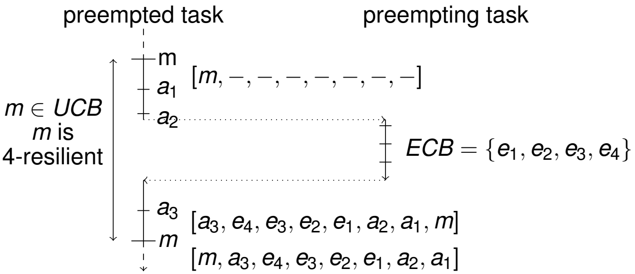

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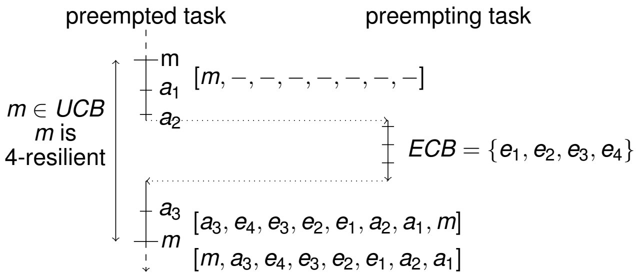

In general: if $|\text{ECB}| \leq l$ then the UCB is not evicted

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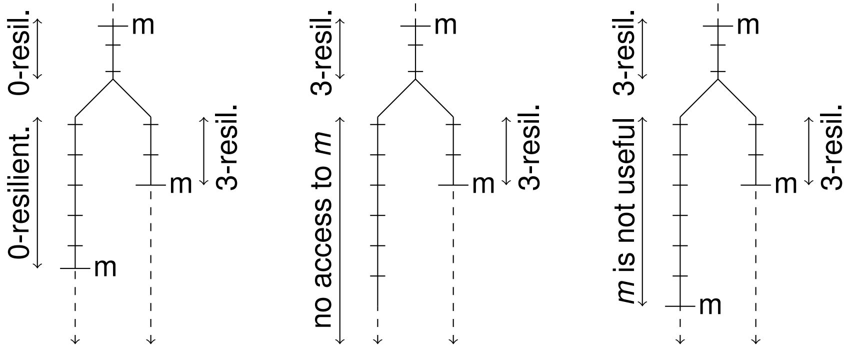

Bounding the CRPD using Resilience

CRPD (Combining UCB and ECB by using Resilience)

$$\left| \overbrace{\underbrace{UCB}_{\textit{useful}} \setminus \underbrace{\{m \mid m \textit{ is } |ECB|\textit{-resilient}\}}_{\textit{remain useful}}}^{\textit{blocks contributing to CRPD}} \right|$$

Bounding the CRPD using Resilience

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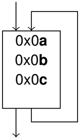
CRPD (Combining UCB and ECB by using Resilience)

$$CRPD \leq BRT \times \left| \overbrace{\underbrace{UCB}_{\textit{useful}} \setminus \underbrace{\{m \mid m \textit{ is } |ECB|\textit{-resilient}\}}_{\textit{remain useful}}}^{\textit{blocks contributing to CRPD}} \right|$$

Bounding the CRPD using Resilience: Example



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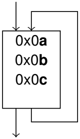

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- $|\text{ECB}| = 1$
- a, b, and c are 1-resilient
- $CRPD^{res}_{\text{UCB\&ECB}} = BRT \times |UCB \setminus \{m \mid m \text{ is } |\text{ECB}|\text{-resilient}\}| = 0$

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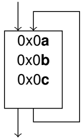

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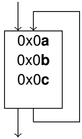

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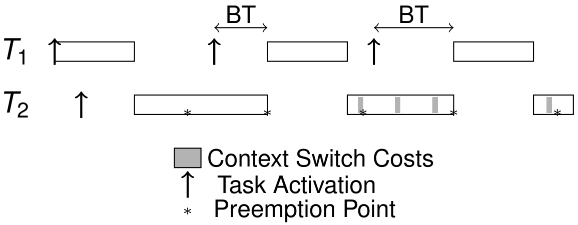
Outline

Deferred Preemption

- Restrict preemptions to a set of predefined *preemption points*.
- Introduces new problem: blocking time, i.e., time until next preemption point is reached.
  Intervals between preemption points $\equiv$ critical sections.



Where to place preemptions points, s.t.

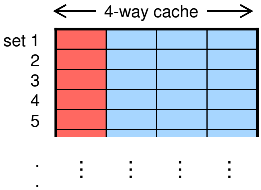
- CRPD is minimized, and
- *Maximum Blocking Time* is minimized?

Analysis to determine maximum blocking time for given set of preemption points: [Lee et al., 1998, Altmeyer et al., 2009]

Cache Partitioning

Additional cache misses are due to interference on the cache.

$\Longrightarrow$ Cache Partitioning eliminates this interference.



- Software-based Cache Partitioning [Wolfe, 1994, Mueller, 1995]:
  - Change layout of instructions and data such that tasks map to disjoint cache sets
  - Particularly difficult for large arrays
- Hardware-based Cache Partitioning [Kirk and Strosnider, 1990, Chiou, 1999]:
  - Partition cache by cache sets and/or cache ways
  - Increases hardware cost
  - Renewed interest in multi-cores with shared caches

Outline

Do existing approaches work for FIFO, PLRU, etc.?

Plain answer: No!

Do existing approaches work for FIFO, PLRU, etc.?

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Plain answer: No!

Counterexample for FIFO [Burguière et al., 2009]:

$$\text{ECBs} = \{\mathbf{x}\} \begin{cases} [b,a] \xrightarrow{a} [b,a] \xrightarrow{e^*} [e,b] \xrightarrow{b} [e,b] \xrightarrow{c^*} [c,e] \xrightarrow{e} [c,e] & \text{2 misses} \\ [\mathbf{x},b] \xrightarrow{a^*} [a,\mathbf{x}] \xrightarrow{e^*} [e,a] \xrightarrow{b^*} [b,e] \xrightarrow{c^*} [c,b] \xrightarrow{e^*} [e,c] & \text{5 misses} \end{cases}$$

- $|\mathrm{UCB}(s)| = 2$
- $|\mathrm{ECB}(s)| = 1$
- associativity $k = 2$
- But: number of additional misses $= 3$

Same result for PLRU.

Idea [Burguière et al., 2009]: Use Relative Competitiveness Results

Some relative competitiveness results:

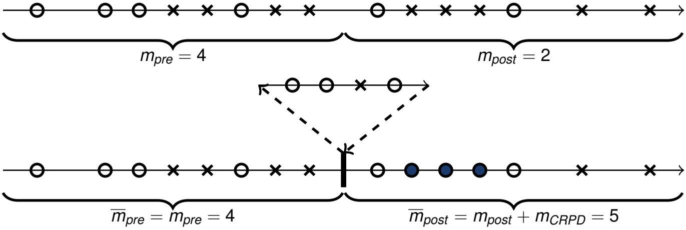
- PLRU(n) is $(1,0)$-miss-competitive relative to LRU($1 + log_2 n$).
- FIFO(n) is $(\frac{n}{n-r+1}, r)$-miss-competitive relative to LRU(r).

$\Longrightarrow$ Performing WCET and CRPD analyses assuming LRU($1 + log_2 n$) replacement should give correct bounds for PLRU(n).

Can we also make use of non-$(1,0)$-competitiveness?

Applying Relative Competitiveness: A sequence of memory accesses

- Notation:
  - m = number of misses
  - $\overline{m}$ = number of misses in the case of preemption



Applying Relative Competitiveness: A sequence of memory accesses

- Notation:
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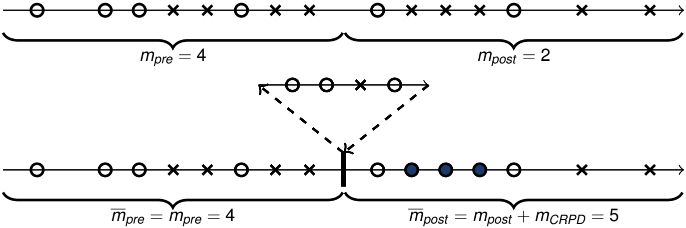
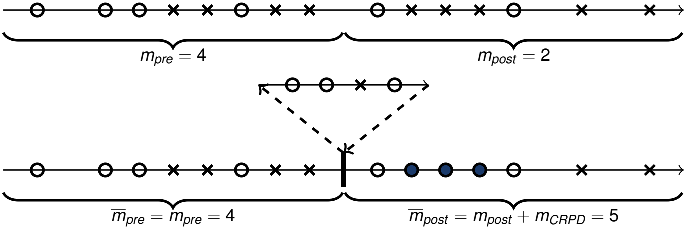


- Assume P(t) is (k, c)-miss-competitive rel. to LRU(s). Then:

$$\overline{m}^{\mathrm{P}(t)} = \overline{m}^{\mathrm{P}(t)}_{pre} + \overline{m}^{\mathrm{P}(t)}_{post}$$

Applying Relative Competitiveness: A sequence of memory accesses

- Notation:
  - $m =$ number of misses
  - $\overline{m} =$ number of misses in the case of preemption



- Assume P(t) is (k, c)-miss-competitive rel. to LRU(s). Then:

$$\begin{aligned} \overline{m}^{\mathrm{P}(t)} &= \overline{m}^{\mathrm{P}(t)}_{pre} + \overline{m}^{\mathrm{P}(t)}_{post} \\ &\leq [k \cdot m^{\mathrm{LRU}(s)}_{pre} + c] + [k \cdot (m^{\mathrm{LRU}(s)}_{post} + m^{\mathrm{LRU}(s)}_{CRPD}) + c] \end{aligned}$$

Applying Relative Competitiveness: A sequence of memory accesses

- Notation:
  - m = number of misses
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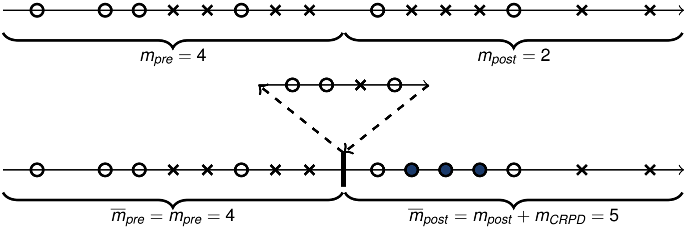

- Assume P(t) is (k, c)-miss-competitive rel. to LRU(s). Then:

$$\begin{aligned}
\overline{m}^{\mathrm{P}(t)} &= \overline{m}_{pre}^{\mathrm{P}(t)} + \overline{m}_{post}^{\mathrm{P}(t)} \\
&\leq [k \cdot m_{pre}^{\mathrm{LRU}(s)} + c] + [k \cdot (m_{post}^{\mathrm{LRU}(s)} + m_{CRPD}^{\mathrm{LRU}(s)}) + c] \\
&= [k \cdot m^{\mathrm{LRU}(s)} + c] + [k \cdot m_{CRPD}^{\mathrm{LRU}(s)} + c]
\end{aligned}$$

Applying Relative Competitiveness

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- Assume P(t) is (k, c)-miss-competitive rel. to LRU(s). Then:

$$\overline{m}^{\mathrm{P}(t)} \leq [k \cdot m^{\mathrm{LRU}(s)} + c] + [k \cdot m_{CRPD}^{\mathrm{LRU}(s)} + c]$$

- In WCET analysis:
  Take into account $k \cdot m^{\mathrm{LRU}(s)} + c$ misses
- In CRPD analysis:
  Take into account $k \cdot m_{CRPD}^{\mathrm{LRU}(s)} + c$ misses

Outline

Summary

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- Preemptive Scheduling desirable, but not for free:
  $\longrightarrow$ Need to bound CRPD
- For LRU, the CRPD can be bounded by analyzing
  - the preempted task: UCB analysis
  - the preempting task: ECB analysis
    - Sound approach rather imprecise
    - Need to couple more tightly with analysis of preempted task
  - both, the preempted and the preempting task
    - “Shallow” combination
    - “Deeper” combination: Resilience analysis
- Approaches do not carry over to FIFO, PLRU, etc. immediately
  - First approach: relative competitiveness

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