# Bounding the Effects of Resource Access Protocols on Cache Behavior

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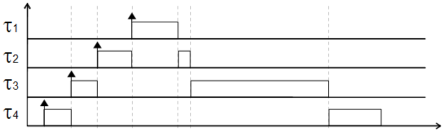
# Task independence assumption

- **Simplifying assumption of independence between tasks**
  - Assumed by most schedulability analysis techniques
    - Constant (and negligible) context-switch costs
- **Broken by reality (e.g., HW acceleration features)**
  - Shared caches and complex pipelines
  - Inter-task interference effects on context switch cost
    - If HW timing is sensitive to execution history then interrupt handling and preemption may influence the execution time of preempted task
  - Even more prominent with the advent of multicore systems

# Cache-Related Preemption Delay

- **Cache-aware schedulabilty analysis techniques**
  - Preempted task may incur additional cache misses
  - Useful cache contents may be evicted by the preempting tasks



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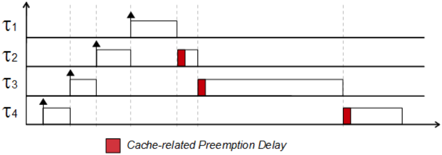
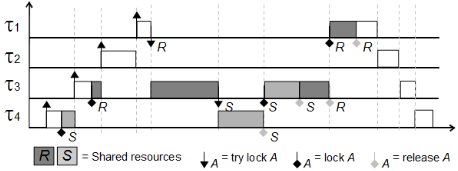



  - *Refill penalty* (CRPD)
  - Depends on both preempted and preempting task
    - *Useful Cache Blocks* ($UCB$)
    - *Used Cache Blocks* ($\overline{UCB}$)
  - Upper bound included in the *response time* of tasks

# Shared Resource Access

- **Priority Inversion**
  - Higher-priority task $\tau_i$ may be **blocked** by lower-priority task $\tau_j$
  - Owing to the need to serialize access to shared resource
    - Potentially *unbounded* duration with risk of *deadlock*




- **Resource access protocols**
  - Bounded priority inversion and (possibly) deadlock avoidance
  - According to each protocol
    - Rich taxonomy (*direct*, *inheritance* and *avoidance* blocking)
    - Bounds on the number of blocking events and duration

# Cache-Related Blocking Delay

- **CRBD**
  - Lower-priority task $\tau_j$ may evict useful cache blocks of higher-priority task $\tau_i$
    - Similar to preemption but in the opposite direction
  - $\tau_i$ may incur a CRBD because of the additional cache misses
    - Blocking events may accumulate during the same activation
- **CRBD vs. CRPD**
  - Could be transformed into a CRPD problem
    - Critical sections ► tasks that may preempt higher priority tasks
  - CRBD as function of $UCB$ of $\tau_i$ and $\overline{UCB}$ of $\tau_j$ but
    - $\overline{UCB}$ limited to execution of $\tau_j$ inside critical sections
    - $UCB$ computed with respect to predefined execution points *(for direct and avoidance blocking)*
    - Transitivity

# CRBD Computation

- **Classical $UCB$ and $\overline{UCB}$ sets**
  - For each task $\tau_i$ at node $n \in CFG(i)$
    - $UCB_i^n = ReachingBlocks_i(n) \cap LiveBlocks_i(n)$
    - $\overline{UCB}_i^n = ReachingBlocks_i(n)$.
- **Assumptions**
  - Total ordering between tasks: $i < j$ if $\pi(\tau_i) > \pi(\tau_j)$
  - $\tau_i$ may access a shared resource $R \in SR_i \subseteq SR_{System}$
    - $cs_{i,k}^R = k^{th}$critical section in $\tau_i$ accessing $R$
  - Shared resources properly nested (can never overlap)
- **CRBD computation**
  - Depends on the actual type of blocking incurred

# CRBD Computation (cont'd)

- **Example of $UCB$ and $\overline{UCB}$ for direct blocking**
  - High priority task $\tau_i$ is directly blocked trying to access $cs^R_{i,k}$
  - Lower-priority task $\tau_j$ is executing inside a critical section $cs^R_{j,h}$

$$UCB^R_{i,k} = UCB^{n_R}_i \text{ where } n_R \text{ is the entry node of } cs^R_{i,k}$$

$$\overline{UCB}_j(cs^R_{j,h}) = ReachingBlocks_j([first\_node, last\_node]_{cs^R_{j,h}})$$

  - Computation of CRBD

$$CRBD = \otimes_\sigma \left(UCB^R_{i,k}, \overline{UCB}_j(cs^R_{j,h})\right) \times \text{miss penalty}$$

  - Where $\otimes_\sigma$ combines the information on $UCB$s and $\overline{UCB}$s
    - According to actual cache associativity and replacement policy
- **Bounds on the CRBD**
  - Leveraging on bounds warranted by resource access protocols
    - Bounds on blocking events ▶ bounds on cache interference

# CRBD under PIP

- **Priority Inheritance**
  - A task inherits the priority of the highest-priority task it is blocking
  - Lowered to the highest inherited priority value upon release
    - Bounded priority inversion
    - Does not prevent deadlocks
    - Direct and inheritance blocking
- **Bound on blocking events**
  - Given $\beta^*_{i,j}$ set of *outermost* critical sections of $\tau_j$ that can block $\tau_i$
  - $\tau_i$ can be blocked by $\tau_j$ for at most the duration of **one** $cs \in \beta^*_{i,j}$
    - By either direct or inheritance blocking
  - Computing *UCB* of $\tau_i$ in case of inheritance blocking
    - Consider any possible node in $CFG(\tau_i)$ ($\sim$ CRPD)

# CRBD under PIP (cont'd)

- **CRBD bound**
  - Direct blocking

$$CRBD_{i,j}^{base} \leq \max_{\substack{R \in SR_j, k \in [1, |cs_i^R|] \\ cs \in \beta^*_{i,j}}} \left\{ \otimes_\sigma \left( UCB_{i,k}^R, \overline{UCB}_j(cs) \right) \right\} \times \text{miss penalty}$$

  - Inheritance blocking
    - $\widehat{\beta}_{i,j} = \{cs | cs \in \beta^*_{i,j} \wedge cs \text{ can block } \tau_i \text{ by inheritance blocking}\}$

$$CRBD_{i,j}^{inherit} \leq \max_{\substack{cs \in \widehat{\beta}_{i,j} \\ n \in CFG(\tau_i)}} \left\{ \otimes_\sigma \left( UCB_i^n, \overline{UCB}_j(cs) \right) \right\} \times \text{miss penalty}$$

  - Then CRBD possibly incurred by $\tau_i$

$$CRBD_i \leq \sum_{j > i} \max \left( CRBD_{i,j}^{base}, CRBD_{i,j}^{inherit} \right)$$

  - PIP also bounds the number of blocking semaphores

# CRBD under PCP

- **Priority Ceiling**
  - Each resource $R$ is statically assigned a *ceiling priority* $ceil(R)$
  - $\tau_i$ can access $R$ if $\pi(i) > ceil(S)\ \forall S \in SR$ currently locked
  - Otherwise the task that blocks $\tau_i$ inherits the ceiling priority of the resource it is locking
    - Bounded priority inversion
    - Prevents deadlock
    - Avoids transitive blocking
    - Introduces avoidance blocking
- **CRBD bound**
  - Exploits the $\beta^*_{i,j}$ and $\widehat{\beta}_{i,j}$ sets defined for PIP
  - Task $\tau_i$ can be blocked at most **once** per activation
    - By either direct, inheritance or avoidance blocking

$$CRBD_i \leq \max_{j>i} \left\{ \max \left( CRBD_{i,j}^{base}, CRBD_{i,j}^{inherit} \right) \right\}$$

# CRBD under ICPP

- **Immediate Ceiling Priority**
  - *Ceiling priorities* are statically assigned as in PCP
  - A task always inherits the ceiling priority of the resource it is locking
  - All tasks with priority lower than or equal to the ceiling priority cannot be scheduled until the resource has been released
    - Bounded priority inversion
    - Prevents deadlock
    - Avoids transitive blocking
    - Adds avoidance blocking
- **Bound on blocking events**
  - Task $\tau_i$ can be blocked at most **once** per activation
    - By either direct, inheritance or avoidance blocking
  - If blocking occurs, it is always before execution
    - **No CRBD**

# Conclusion

- **Included in RTA iterative equation**

$$w_i^{n+1} = C_i + B_i + \beta_i + \sum_{j \in hp(i)} \left\lceil \frac{w_i^n}{T_j} \right\rceil \times (C_j + \gamma_j)$$

  - However worst-case $B_i$ and $\beta_i$ not necessarily occur altogether
  - Advanced approaches to CRPD like *Resilience Analysis*
    - Would require a combined computation of $\gamma_i$ and $\beta_i$
- **CRBD bounds**
  - The actual CRBD effect may be small
    - Simple test ▶ 8 out of 38 misses due to direct blocking
      ▶ 3 out of 12 misses due to inheritance blocking
    - Still important for schedulability analysis that seeks accuracy
  - CRBD as a selection criterion for resource access protocol
    - The use of ICPP is free from CRBD