

Abstract Interpretation of FIFO Replacement

Daniel Grund Jan Reineke

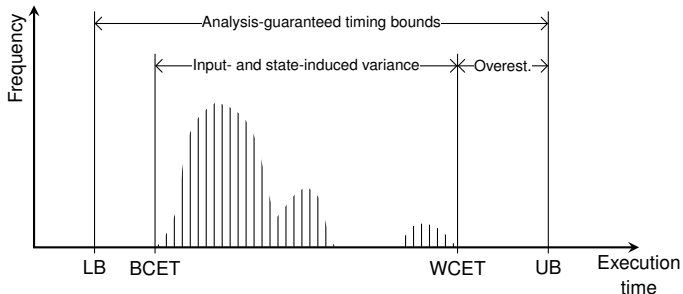
Saarland University, Saarbrücken, Germany

Static Analysis Symposium 2009



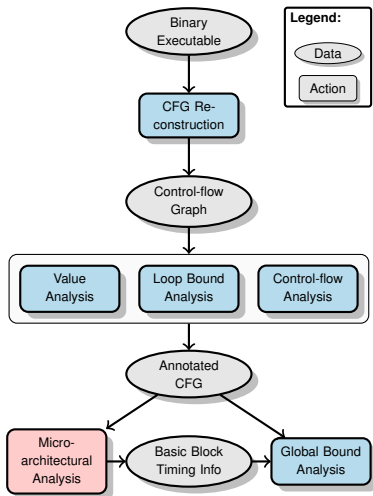
- 1 Introduction & Motivation
 - Timing Analysis
 - Cache Analysis
- 2 Abstract Interpretation of FIFO
 - Challenge FIFO Replacement
 - Domain Cooperation
 - Must Analysis
 - May Analysis
- 3 Evaluation
 - Related Work
 - Analysis Precision
- 4 Summary

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- Execution time depends on
 - ▶ program input
 - ▶ initial hardware state
- Bounds required for schedulability analysis of real-time systems

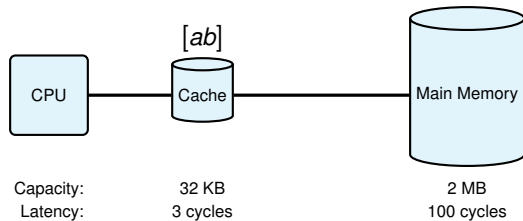
Static Timing-Analysis Framework



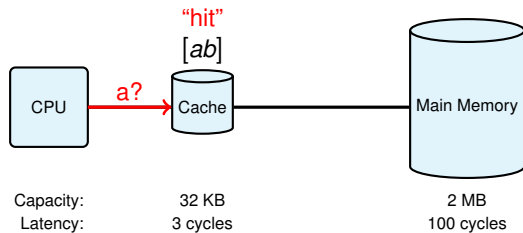
Framework implemented by *aiT* of AbsInt

Micro-architectural analysis

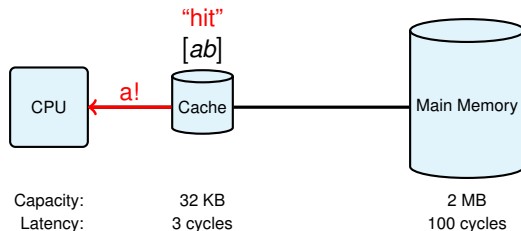
- models pipeline, caches, buses, etc.
- derives bounds on BB exec. times
- is an abstract interpretation with a huge domain
- is the computationally most expensive module



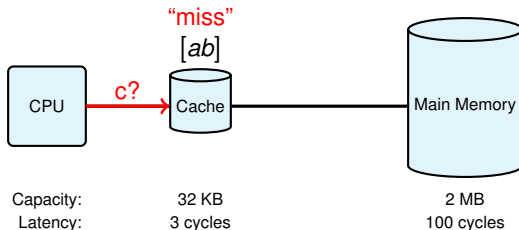
- Caches transparently buffer memory blocks



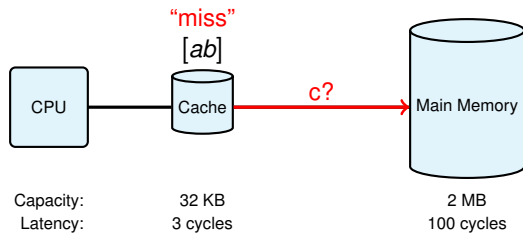
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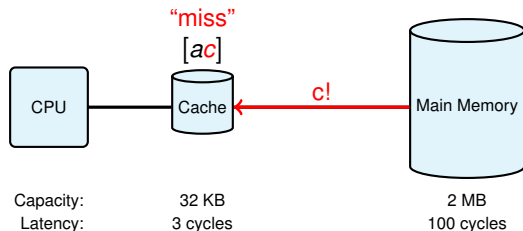
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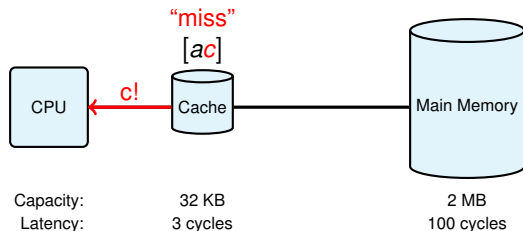
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- Caches transparently buffer memory blocks
- Replacement policy *dynamically* decides which element to replace
 - LRU least recently used
 - PLRU pseudo LRU
 - FIFO first-in first-out
- Have great influence on abstraction and (obtainable) analysis precision



- Caches transparently buffer memory blocks
- Replacement policy *dynamically* decides which element to replace
 - LRU least recently used
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- Have great influence on abstraction and (obtainable) analysis precision

- Cache performance has great influence on overall performance
- Need tight bounds on cache performance
- Otherwise derived timing bounds may be useless:
 - ▶ tasks are deemed not schedulable
 - ▶ waste of hardware resources

- Application: Buffers with transparent replacement
 - ▶ Instruction- and data-caches
 - ▶ Branch target buffers (BTB, BTIC)
 - ▶ Translation lookaside buffers (TLB)

- derives **approximations to cache contents** at each program point
- in order to **classify memory accesses** as cache hits or cache misses

Must-information

- **Under**approximation of cache contents
- Used to soundly classify cache **hits**

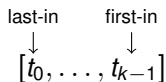
May-information

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- Used to soundly classify cache **misses**

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Concrete Semantics: What is FIFO?

- State of FIFO cache of size k : $s \in \mathcal{S} := \mathcal{T}^k$



- Examples:

$$[d, c, b, a] \xrightarrow[\text{hit}]{c} [d, c, b, a]$$

$$[d, c, b, a] \xrightarrow[\text{miss}]{e} [e, d, c, b]$$

- Update: $\mathcal{U}_{\mathcal{S}} : \mathcal{S} \times \mathcal{T} \rightarrow \mathcal{S}$

$$\mathcal{U}_{\mathcal{S}}([t_0, \dots, t_{k-1}], t) := \begin{cases} [t_0, \dots, t_{k-1}] & : \exists i : t = t_i & \text{"cache hit"} \\ [t, t_0, \dots, t_{k-2}] & : \text{otherwise} & \text{"cache miss"} \end{cases}$$

Challenge: How to Predict Hits?

- Consider a FIFO cache with unknown contents

$$[?, ?, ?, ?] \xrightarrow[\text{hit}]{a} [?, a, ?, ?] \xrightarrow[\text{hit}]{b} [?, a, ?, b]$$

$$[?, ?, ?, ?] \xrightarrow[\text{hit}]{a} [?, ?, ?, a] \xrightarrow[\text{miss}]{b} [b, ?, ?, ?]$$

- If *a* may be a hit, then *b* may evict *a*

⇒ Can only predict hits for most recently accessed element

- Can one do better?

$$[?, ?, ?, ?] \xrightarrow[\text{miss}]{a} [a, ?, ?, ?] \xrightarrow[\text{miss}]{b} [b, a, ?, ?]$$

- If *a* is a miss, then *b* cannot evict *a*

⇒ Can predict hits for *a* until *k* further misses might have happened

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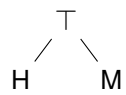
⇒ Can predict hits for *a* until *k* further misses might have happened

⇒ Need may-information to obtain precise must-information

- Framework for static cache analysis
 - ▶ policy independent
 - ▶ couples must- and may-analyses
 - ▶ analyses cooperate via “update reduction”
- FIFO must-analysis
 - ▶ can profit from may-information
 - ▶ hence, also better must-information
- FIFO may-analysis
 - ▶ utilizes order of hits and misses
 - ▶ more precise than prior analyses

Domain: $Fifo := Must \times May$

Classification: $Class := \{H, M\}^\top$



H : cache hit
M : cache miss
 \top : unclassified

$C_{Fifo} : Fifo \times \mathcal{T} \rightarrow Class$

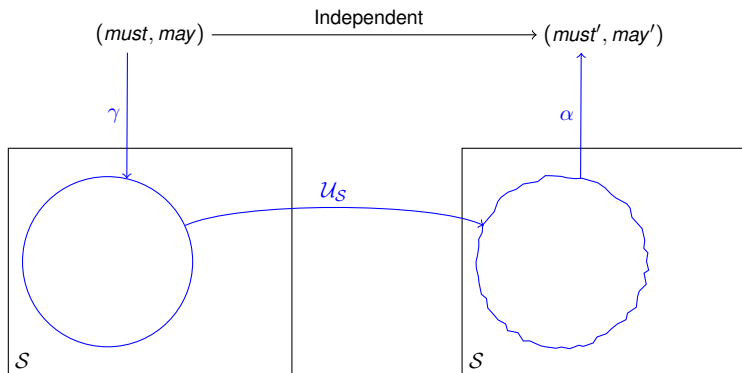
$C_{Fifo}((must, may), t) := C_{Must}(must, t) \sqcap C_{May}(may, t)$

Domain Cooperation via Update Reduction

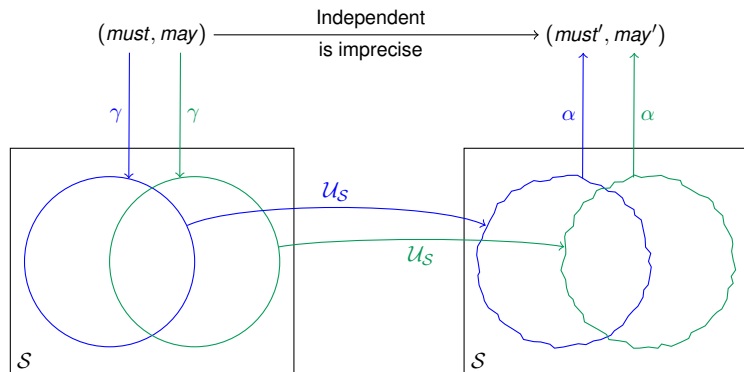
$(must, may) \xrightarrow{\text{Independent}} (must', may')$



Domain Cooperation via Update Reduction



Domain Cooperation via Update Reduction

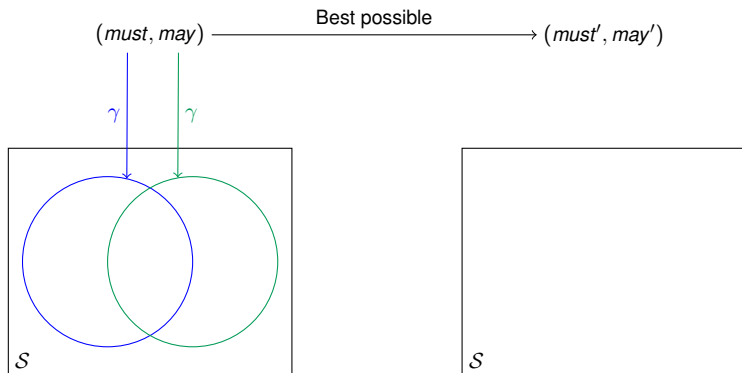


Domain Cooperation via Update Reduction

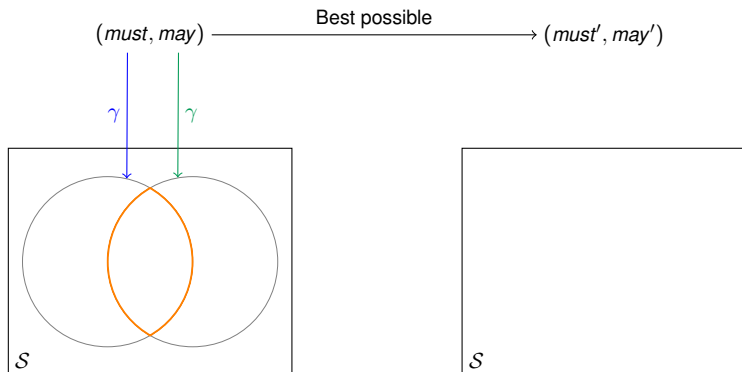
$(must, may)$ $\xrightarrow{\text{Best possible}}$ $(must', may')$



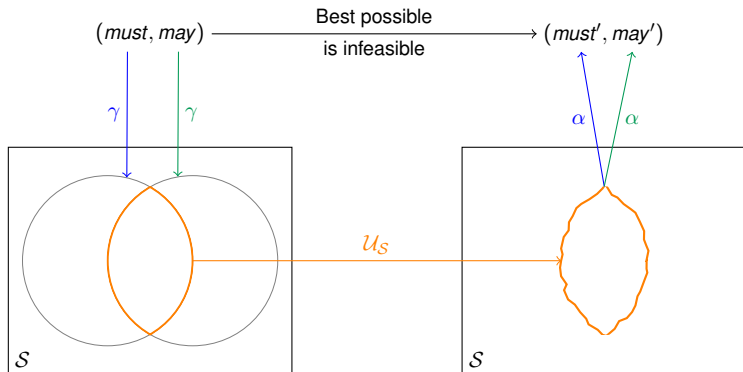
Domain Cooperation via Update Reduction



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Domain Cooperation via Update Reduction

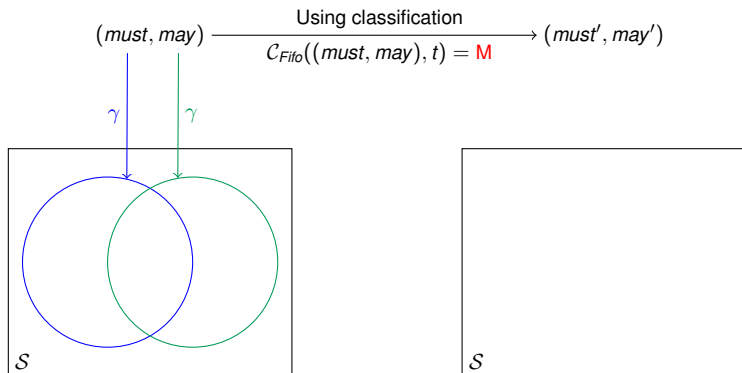


Domain Cooperation via Update Reduction

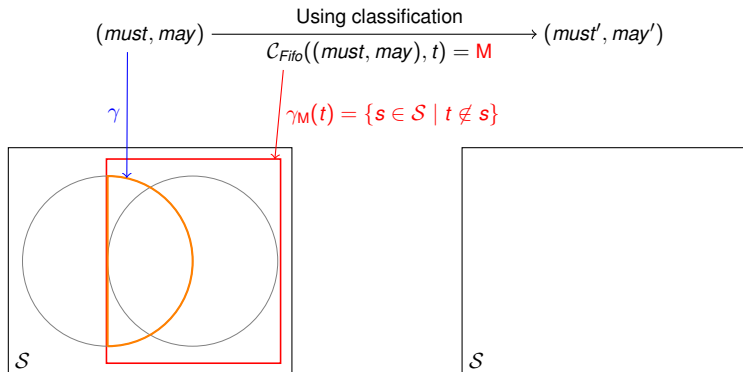
$$(must, may) \xrightarrow[\mathcal{C}_{Fifo}((must, may), t) = \mathbf{M}]{\text{Using classification}} (must', may')$$



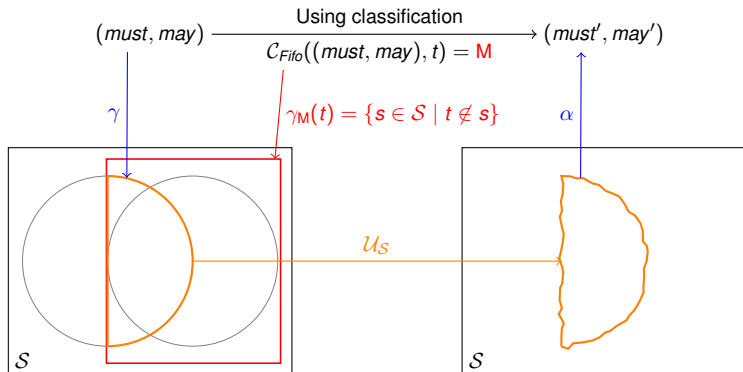
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Domain Cooperation via Update Reduction



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Must-Analysis: Potential Misses

- For FIFO, a newly inserted element is evicted after k misses
- ⇒ Maintain **upper bound** on number of misses: **Potential misses**
- Abstract must-domain closely resembles the concrete domain

$$Must_{Fifo_k} := [T_0, \dots, T_{k-1}],$$

where $T_i \in \mathcal{P}(\mathcal{I})$, $T_i \cap T_j = \emptyset$, and $\sum |T_i| \leq k$.

- $t \in T_i \Rightarrow$ at most i misses since insertion of t
- Concretization example

$$\gamma(\left[\{f\}, \emptyset, \{a, c\}, \{b\}\right]) = \{[f, c, a, b], [f, a, c, b]\}$$

$$\mathcal{U}_{Must} : Must \times \mathcal{T} \times Class \rightarrow Must$$

$$\mathcal{U}_{Must}([T_0, \dots, T_{k-1}], t, cl) := \begin{cases} [\emptyset, T_0, \dots, T_{k-2} \cup \{t\}] & : cl = T \\ [T_0, \dots, T_{k-1}] & : cl = H \\ [\{t\}, T_0, \dots, T_{k-2}] & : cl = M \end{cases}$$

- **Misses** classified by may-analysis
- Last case only possible due to **domain cooperation**

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May-Analysis: Definite Misses

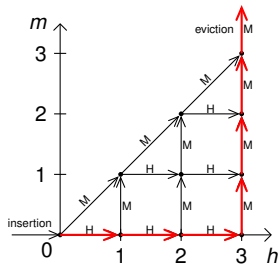
- How to predict misses?
- ⇒ Maintain **lower bound** on number of misses: **Definite misses**
- Initially, anything might be cached
- To classify a miss for an *individual* access, one needs to predict k other misses first

Lemma

A newly inserted element is evicted after accesses to at most $2k - 1$ pairwise different elements.

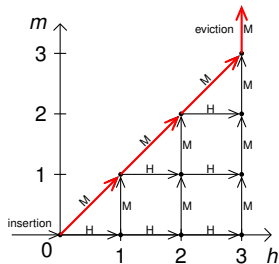
May-Analysis: Idea “Early Misses”

- Initial state: $[x, c, b, a]$
- Sequences of different length:
 - ▶ $\langle a, b, c, e, f, g, h \rangle$
- Common final state: $[h, g, f, e]$



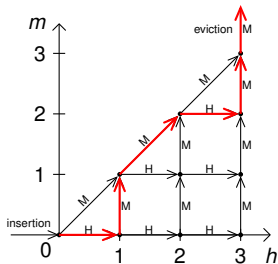
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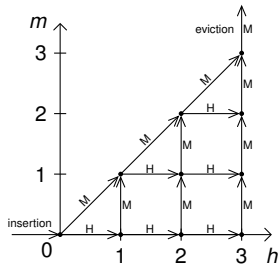
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⇒ Sequences differ in number of hits

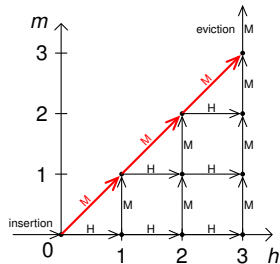


May-Analysis: Idea “Early Misses”

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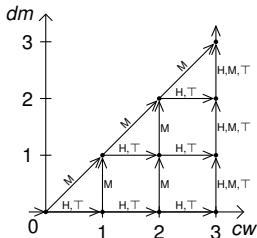
- “Early misses”

- ▶ preclude hits to thereby evicted elements
- ▶ reduce number of possible accesses between insertion and eviction

⇒ Order of hits and misses is important

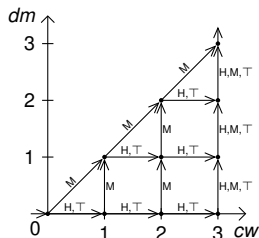
May-Analysis: Domain

- May analysis approximates position in triangle
- Unclassified access → “take the longer way”



- For each element t , the analysis maintains:

- A* Set of *Potentially Accessed Elements*
- dm* Number of *Definite Misses*
- cw* Number of *Covered Ways* (Covered Cache Positions)



- Assume sequence $\langle x, a, b, c \rangle$ and all accesses are unclassified
- Then for x one has:
 - $A = \{a, b, c\}$ a, b and c might have been accessed since the last insertion of x
 - $dm = 0$ 0 misses have definitely happened since the last insertion of x
 - $cw = 3$ Assuming that all unclassified accesses were hits, then 3 elements of A must be cached
- Consider next access to d

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- How many misses would FIFO have if LRU has m_{LRU} misses?

Definition: Relative Competitiveness

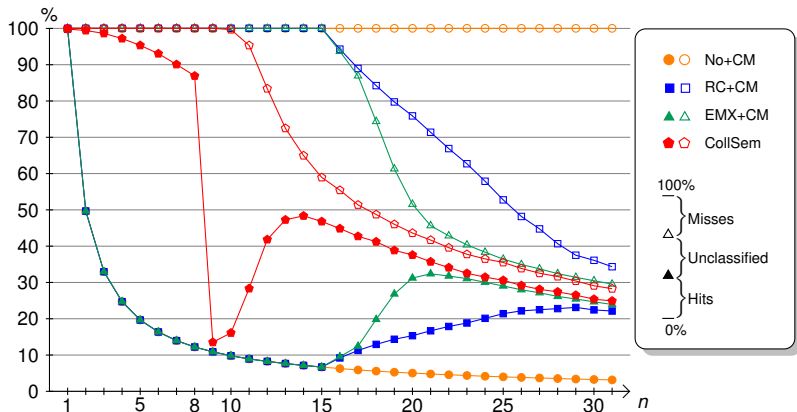
Policy P is (f, c) miss-competitive relative to policy Q if

$$m_P(p, s) \leq f \cdot m_Q(q, s) + c$$

for all access sequences s and compatible cache states p, q .

- E.g. LRU($2k - 1$) is $(1, 0)$ miss-competitive vs. FIFO(k)
⇒ LRU($2k - 1$) may-analysis can be used for FIFO(k) may analysis

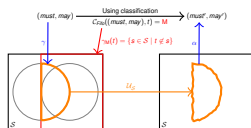
- **Must-analysis:**
 - CM Canonical must-analysis (this paper)
- **May-analyses:**
 - No None
 - RC Based on relative competitiveness
 - EMX Early Miss eXploitation (this paper)
- **Instantiations of cache analysis framework:**
 - ▶ No+CM
 - ▶ RC+CM
 - ▶ EMX+CM
- **Synthetic benchmarks:**
 - ▶ Random access sequences and program fragments



- Average guaranteed hit- and miss-rates for a cache of size 8
- n is number of pairwise different elements that are accessed

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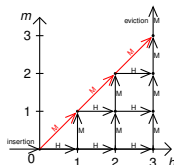
- Cache analysis framework
 - Couple several analyses
 - Cooperation via classifications



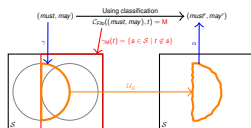
- Canonical FIFO must-analysis
 - Potential misses

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- EMX FIFO may-analysis
 - Definite misses
 - Early Miss eXploitation



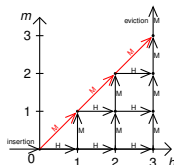
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- EMX FIFO may-analysis
 - Definite misses
 - Early Miss exploitation



Thank you for listening. Questions?



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The worst-case execution time problem—
overview of methods and survey of tools

Transactions on Embedded Computing Systems, 7(3), 2008



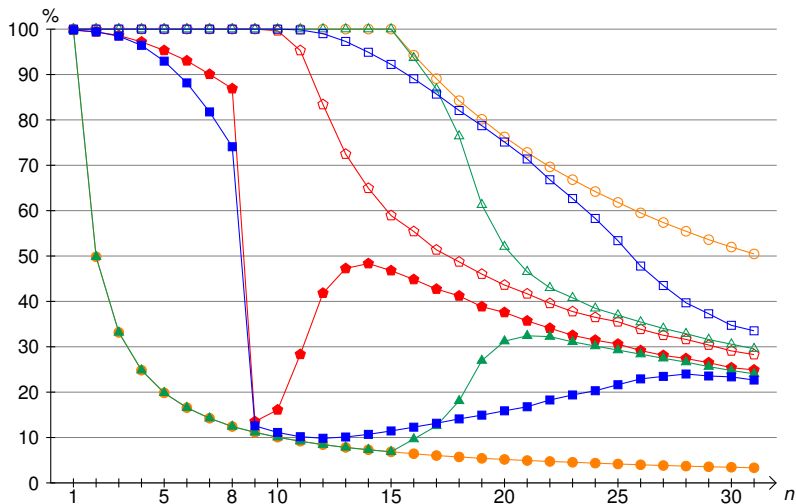
J. Reineke and D. Grund

Relative competitive analysis of cache replacement policies

LCTES 2008

- Bounds on number of cache misses:
 - Ghosh Cache Miss Equations, loop nests
 - Chatterjee Exact model of cache behavior for loop nests
- Classification of individual accesses:
 - Mueller By “static cache simulation”
 - Li By integer linear programming
 - Ferdinand By abstract interpretation
- Only for LRU caches

What About The Gap for $n \leq k$?



- Yes, a FIFO of size k , is (k,k) sensitive

Definition: Sensitivity

Policy P is (f, c) miss-sensitive if

$$m_P(p, s) \leq f \cdot m_P(p', s) + c$$

for all access sequences s and all cache states p, p' .

⇒ For FIFO of size 4, execution time may differ by a factor of 3



R. Wilhelm et al.

Memory Hierarchies, Pipelines, and Buses for
Future Architectures in Time-critical Embedded Systems

IEEE Transactions on CAD of Integrated Circuits and Systems 2009