Timing analysis and timing predictability

Caches in WCET Analysis

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January 18, 2011

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Outline

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1 Caches

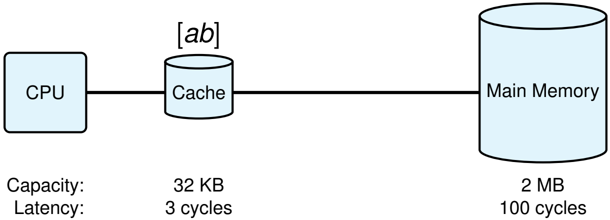
2 Cache Analysis for Least-Recently-Used

3 Beyond Least-Recently-Used
- Predictability Metrics
- Relative Competitiveness
- Sensitivity – Caches and Measurement-Based Timing Analysis

4 Summary

Caches

- Small but very fast memories that buffer part of the main memory
- Bridge the gap between speed of CPU and main memory



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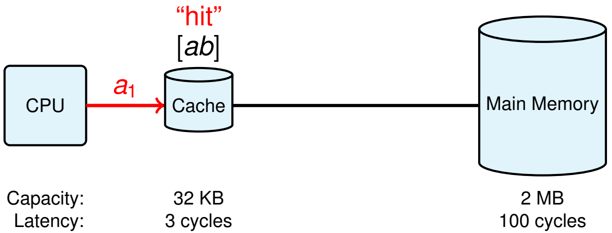

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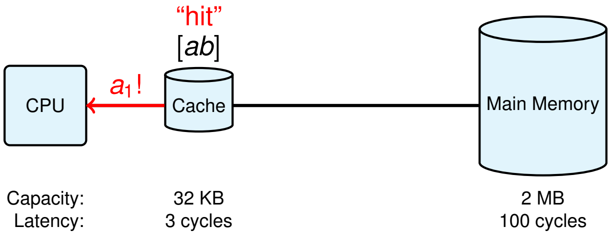

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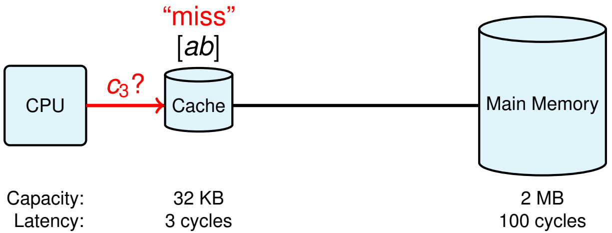

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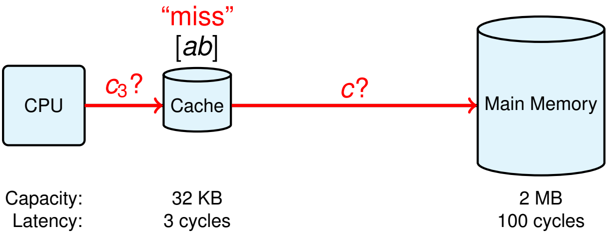

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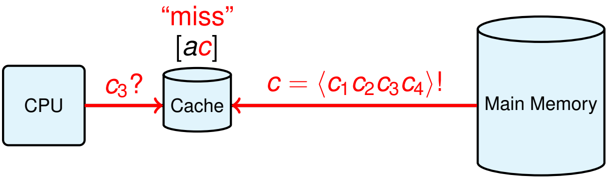

Capacity:	32 KB	2 MB
Latency:	3 cycles	100 cycles

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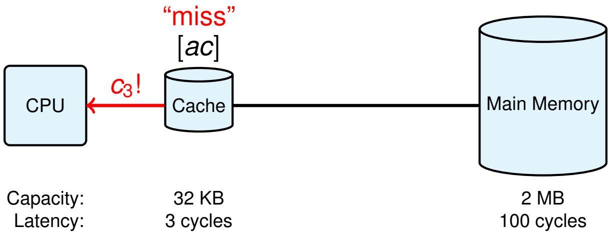

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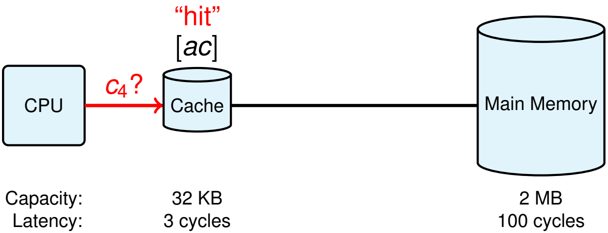

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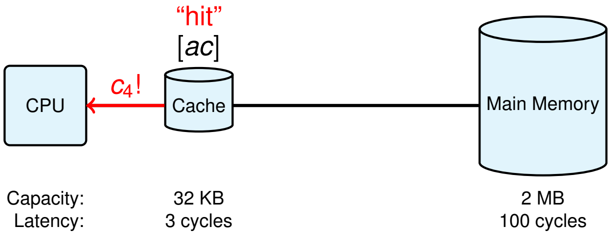

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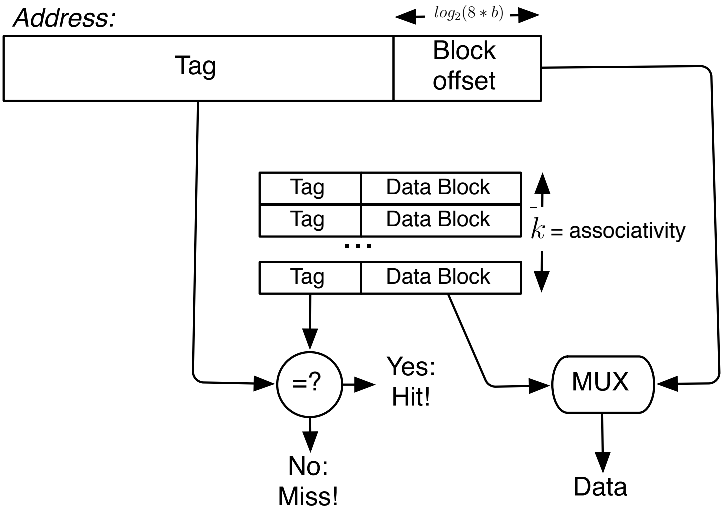
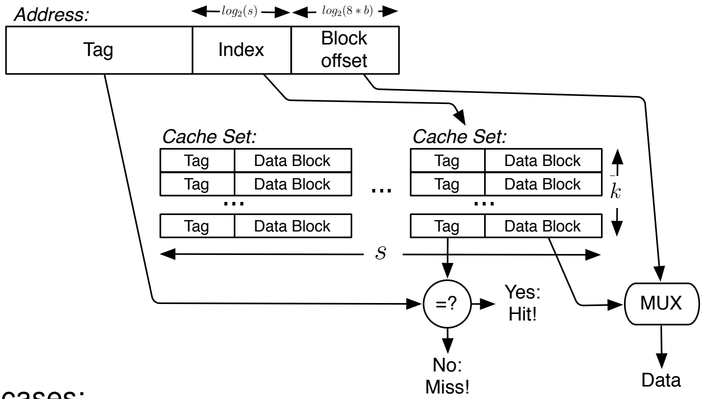
Fully-Associative Caches



Set-Associative Caches



Special cases:

- direct-mapped cache: only one line per cache set
- fully-associative cache: only one cache set

Cache Replacement Policies

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- Least-Recently-Used (LRU) used in
  INTEL PENTIUM I and MIPS 24K/34K
- First-In First-Out (FIFO or Round-Robin) used in
  MOTOROLA POWERPC 56X, INTEL XSCALE, ARM9, ARM11
- Pseudo-LRU (PLRU) used in
  INTEL PENTIUM II-IV and POWERPC 75X
- Most-Recently-Used (MRU) as described in literature

Each cache set is treated independently:
⟶ Set-associative caches are compositions of fully-associative caches.

Outline

Cache Analysis

Two types of cache analyses:

1. Local guarantees: classification of individual accesses
   - May-Analysis $\longrightarrow$ Overapproximates cache contents
   - Must-Analysis $\longrightarrow$ Underapproximates cache contents
2. Global guarantees: bounds on cache hits/misses

- Cache analyses almost exclusively for LRU
- In practice: FIFO, PLRU, ...

Abstract Interpretation in Timing Analysis

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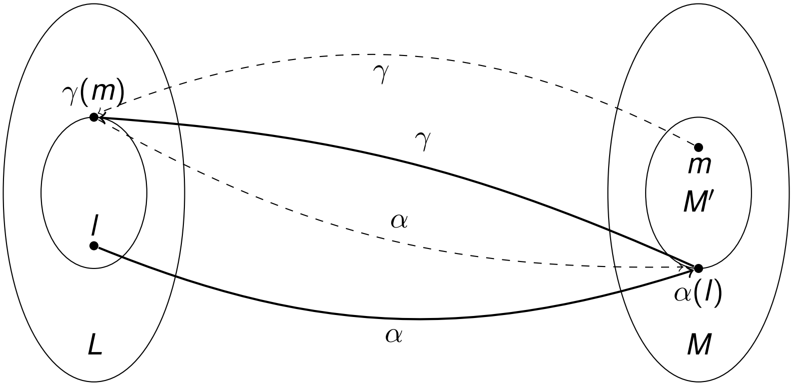
- Abstract interpretation is always based on the semantics of the analyzed language.
- A semantics of a programming language that talks about time needs to incorporate the execution platform!
- Static timing analysis is thus based on such a semantics.

Galois Connection

- Abstraction function α
- Concretization function γ

$\Rightarrow \forall m' \in M' : \gamma(m') = \gamma(m)$

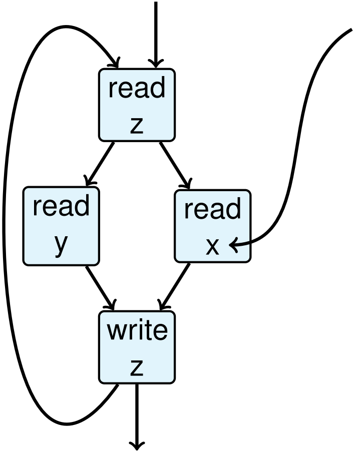


Abstract Interpretation in Timing Analysis

Determines:

1. invariants about the values of variables (in registers, on the stack)
   - to compute loop bounds
   - to eliminate infeasible paths
   - to determine effective memory addresses
2. invariants on architectural execution state
   - Cache contents $\Rightarrow$ predict hits and misses
   - Pipeline states $\Rightarrow$ predict or exclude pipeline stalls

Challenges for Cache Analysis



Always a cache hit/always a miss?

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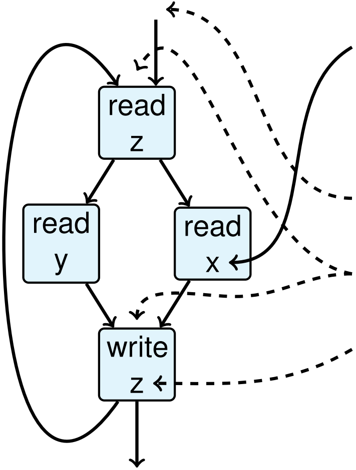
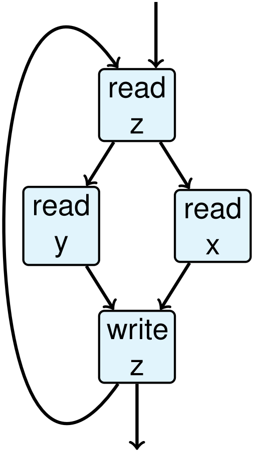


Always a cache hit/always a miss?

1. Initial cache contents unknown.
2. Different paths lead to these points.
3. Cannot resolve address of *z*.

Deriving Invariants about Cache States using Abstract Interpretation



Collecting Semantics =
set of states at each program point that any execution may encounter there

Two approximations:

	Collecting Semantics	uncomputable
$\subseteq$	Cache Semantics	computable
$\subseteq$	γ(Abstract Cache Sem.)	efficiently computable

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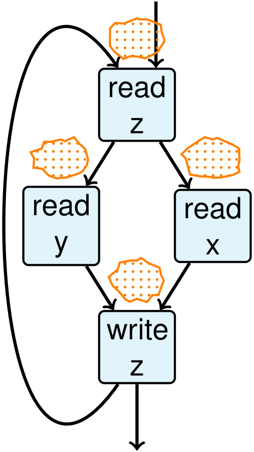

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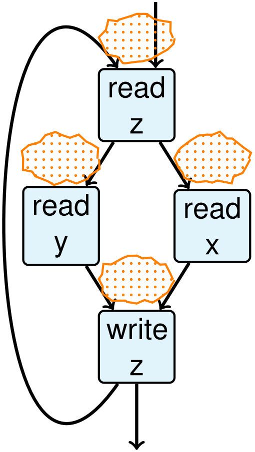

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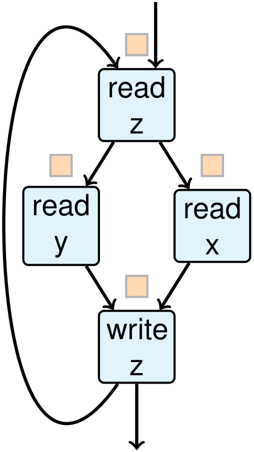

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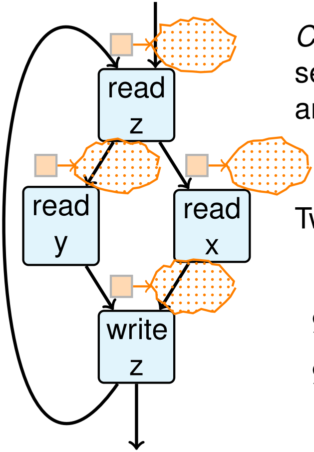

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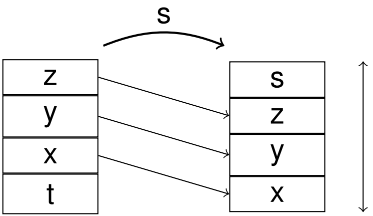
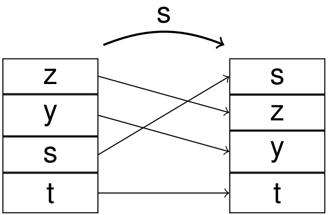
Least-Recently-Used (LRU): Concrete Behavior

“Cache Miss”:



LRU has notion of age

“Cache Hit”:



LRU: Must-Analysis: Abstract Domain

- Used to predict *cache hits*.
- Maintains *upper bounds on ages* of memory blocks.
- Upper bound $\leq$ associativity $\longrightarrow$ memory block definitely cached.

Example

Abstract state:

{x}	age 0
{}	
{s,t}	
{}	age 3

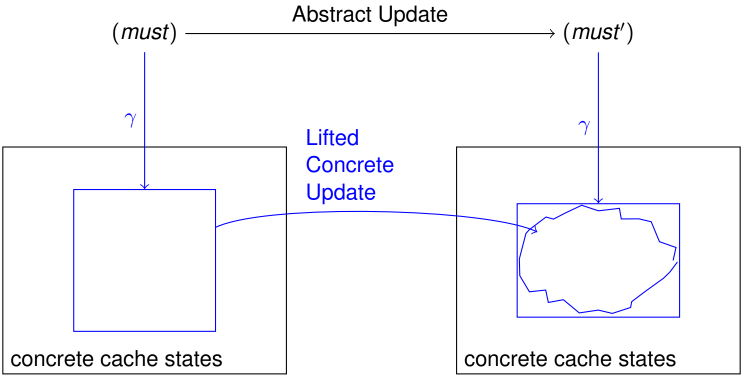
...and its interpretation:

Describes the set of all concrete cache states in which x, s, and t occur,

- x with an age of 0,
- s and t with an age not older than 2.

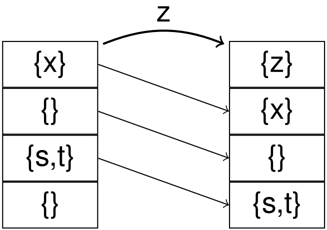
$$\gamma([\{x\},\{\},\{s,t\},\{\}]) = \{[x,s,t,a],[x,t,s,a],[x,s,t,b],\ldots\}$$

Sound Update – Local Consistency

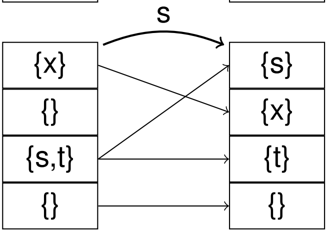


LRU: Must-Analysis: Update

"Potential Cache Miss":



"Definite Cache Hit":



Why does *t* not age in the second case?

Must-Analysis for LRU: Join

Need to combine information where control-flow merges.

Join should be conservative:

- $\gamma(A) \subseteq \gamma(A \sqcup B)$
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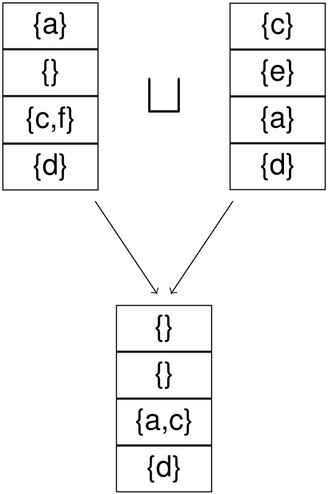
"Intersection + Maximal Age"



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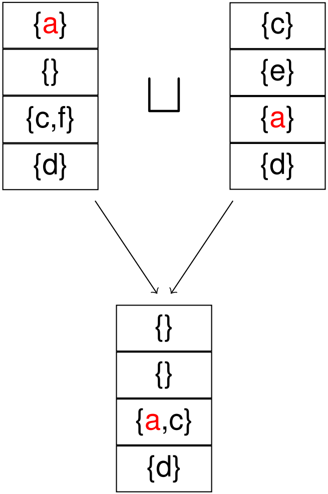

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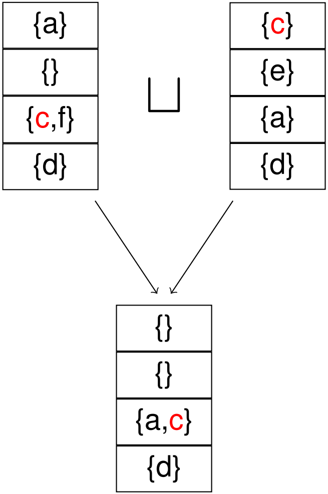

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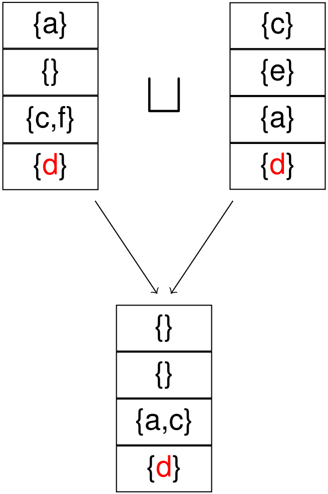

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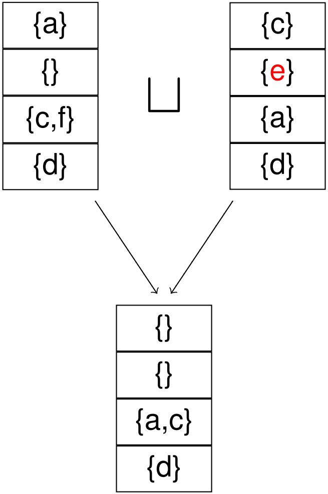

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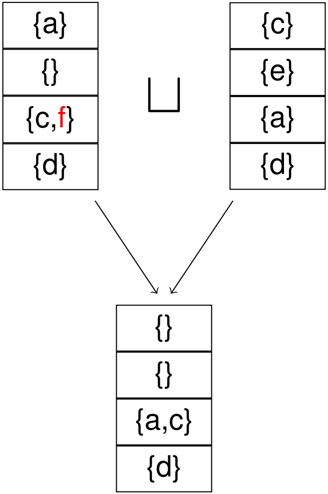

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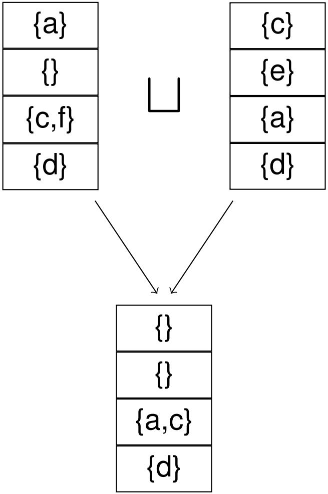

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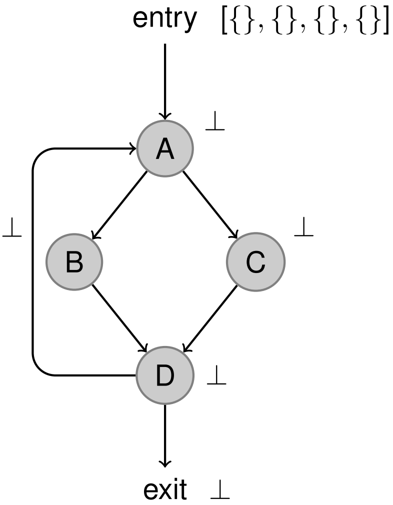
How many memory blocks can be in the must-cache?

Example: Must-Analysis



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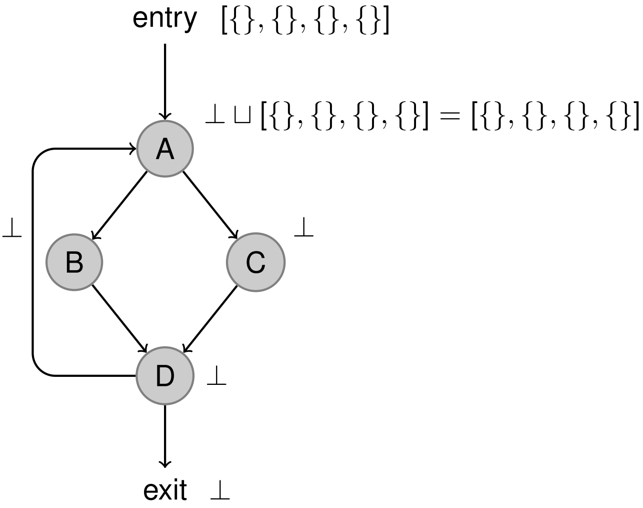

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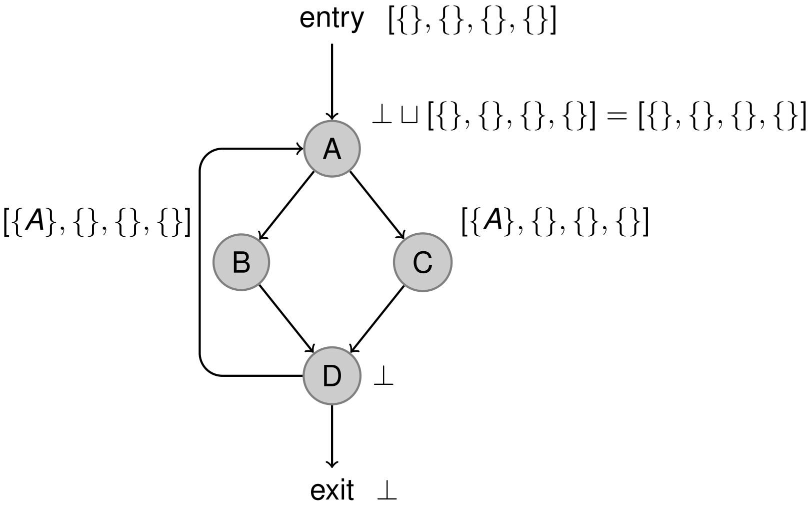

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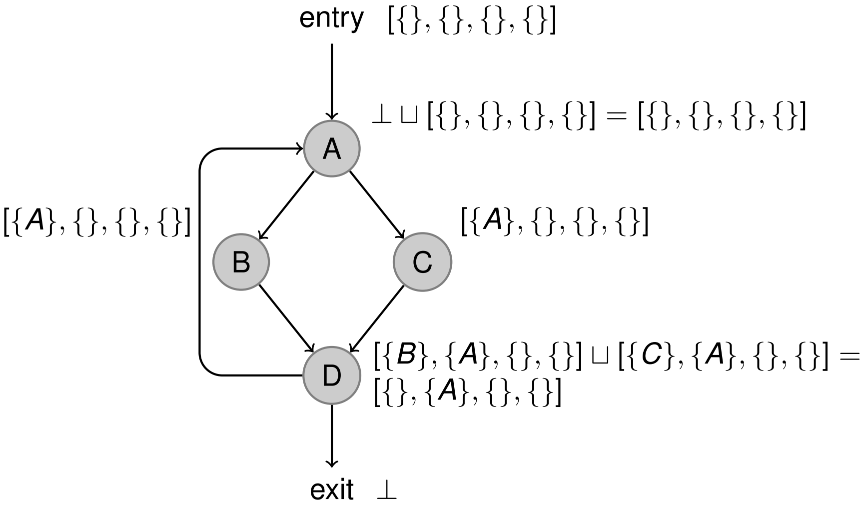

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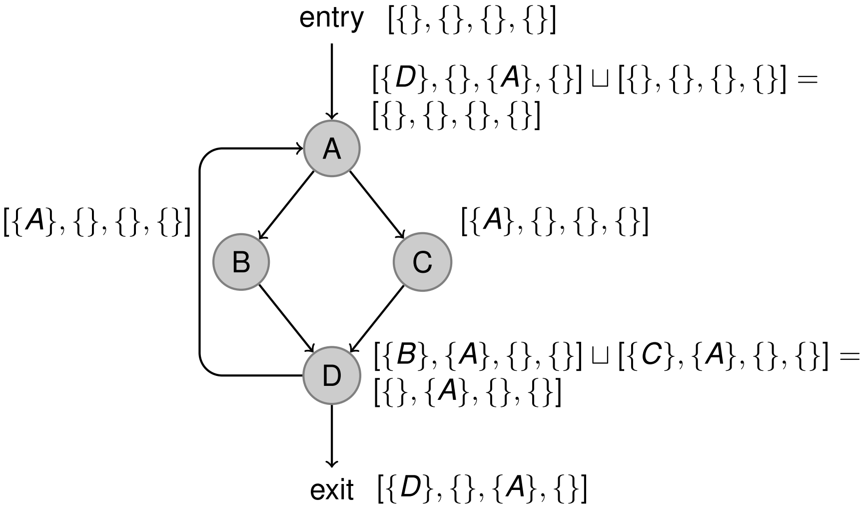
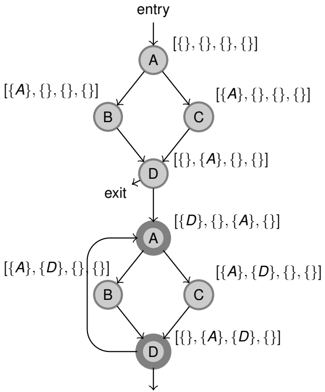


No cache hits can be predicted :-(

Context-Sensitive Analysis/Virtual Loop-Unrolling

- Problem:
  - The first iteration of a loop will always result in cache misses.
  - Similarly for the first execution of a function.
- Solution:
  - Virtually Unroll Loops: Distinguish the first iteration from others
  - Distinguish function calls by calling context.



Virtually unrolling the loop once:

- Accesses to *A* and *D* are provably hits after the first iteration
- Accesses to *B* and *C* can still not be classified. Within each execution of the loop, they may only miss once.
  $\longrightarrow$ Persistence Analysis

LRU: May-Analysis: Abstract Domain

- Used to predict *cache misses*.
- Maintains *lower bounds on ages* of memory blocks.
- Lower bound $\geq$ associativity
  $\longrightarrow$ memory block definitely *not* cached.

Example

...and its interpretation:

Abstract state:

{x,y}	age 0
{}	
{s,t}	
{u}	age 3

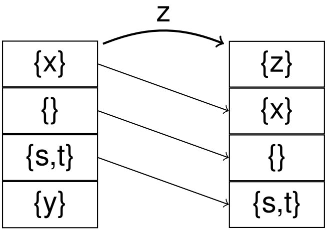
Describes the set of all concrete cache states in which no memory blocks except *x*, *y*, *s*, *t*, and *u* occur,

- *x* and *y* with an age of at least 0,
- *s* and *t* with an age of at least 2,
- *u* with an age of at least 3.

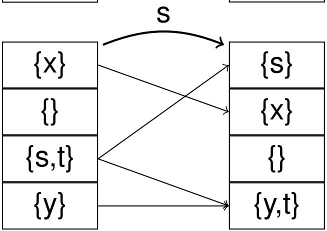
$$\gamma([\{x,y\},\{\},\{s,t\},\{u\}]) = \{[x,y,s,t],[y,x,s,t],[x,y,s,u],\ldots\}$$

LRU: May-Analysis: Update

“Definite Cache Miss”:



“Potential Cache Hit”:



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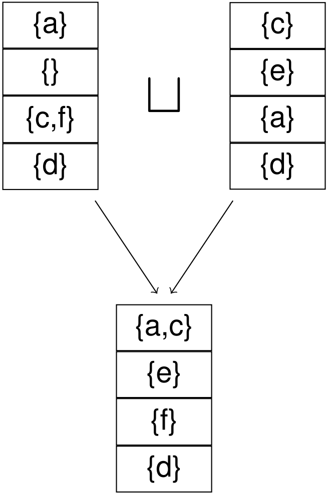

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"Union + Minimal Age"

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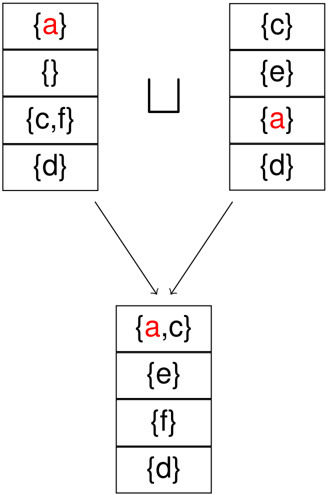

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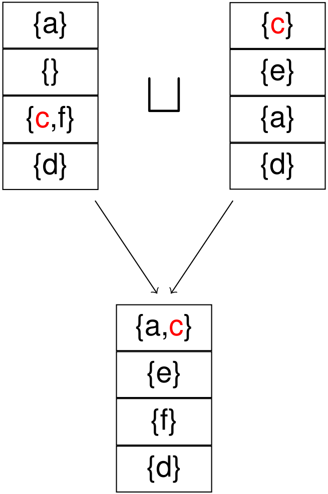

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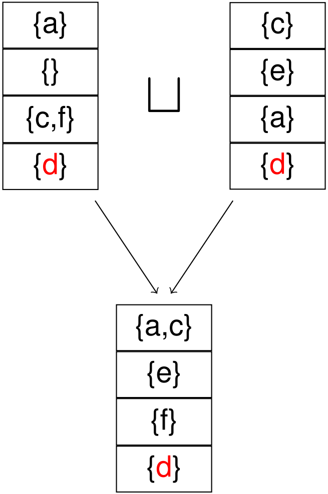

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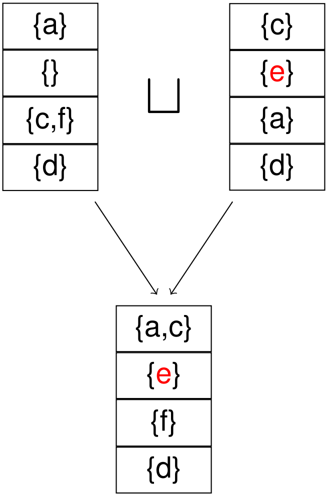

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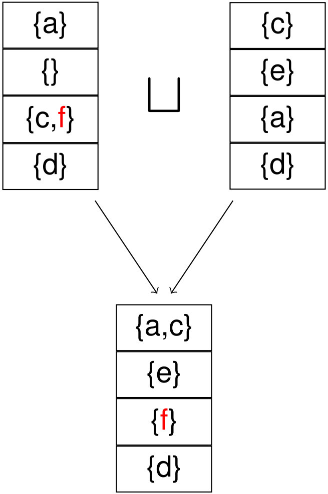
LRU: May-Analysis: Join

Need to combine information where control-flow merges.



Join should be conservative:

- $\gamma(A) \subseteq \gamma(A \sqcup B)$
- $\gamma(B) \subseteq \gamma(A \sqcup B)$

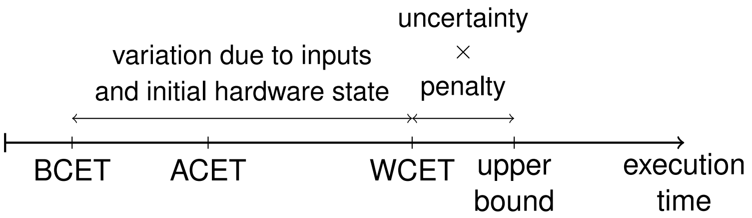
"Union + Minimal Age"

Outline

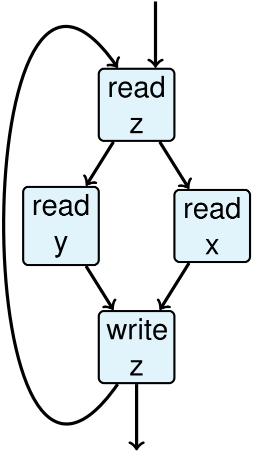
Outline

Uncertainty in WCET Analysis

- Amount of uncertainty determines precision of WCET analysis
- Uncertainty in cache analysis depends on replacement policy



Uncertainty in Cache Analysis



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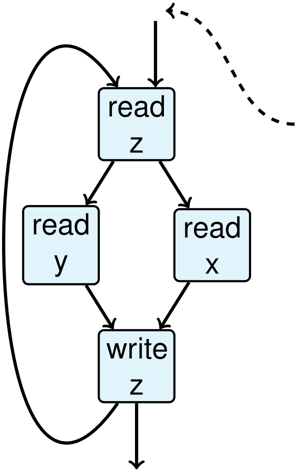
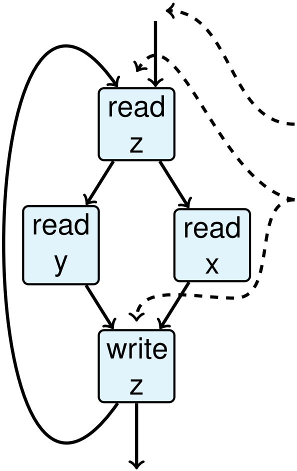


1. Initial cache contents unknown.

Uncertainty in Cache Analysis



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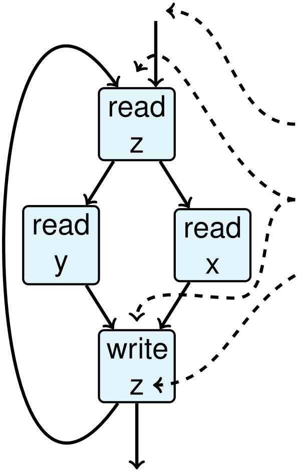
Uncertainty in Cache Analysis



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3. Cannot resolve address of *z*.

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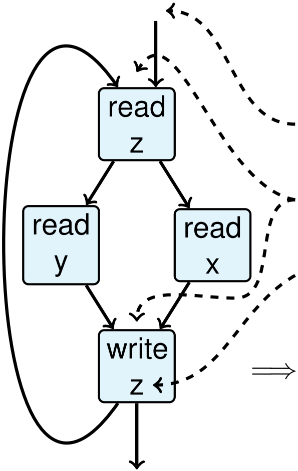
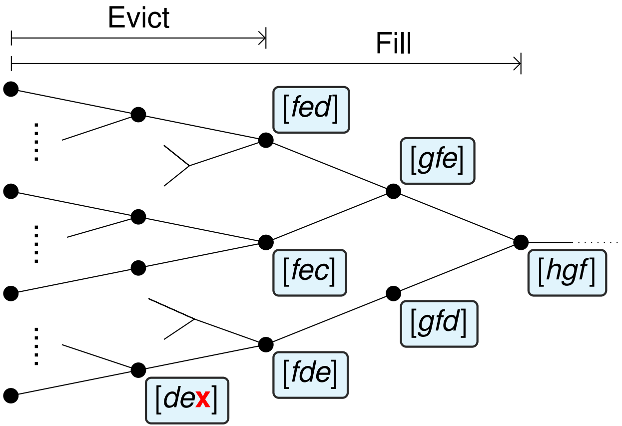


1. Initial cache contents unknown.
2. Need to combine information.
3. Cannot resolve address of *z*.

$\Longrightarrow$ Amount of uncertainty determined by ability to recover information

Predictability Metrics



Sequence: $\langle$a, . . . , e, f, g, h$\rangle$

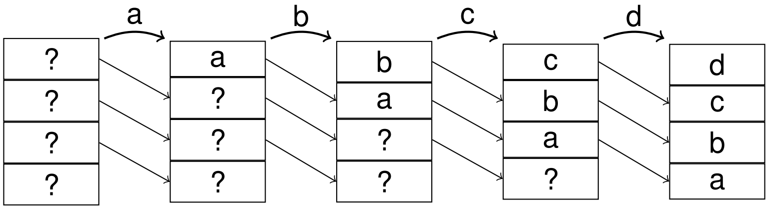
Meaning of Metrics

- Evict
  - Number of accesses to obtain *any may*-information.
  - I.e. when can an analysis predict any cache misses?
- Fill
  - Number of accesses to complete *may*- and *must*-information.
  - I.e. when can an analysis predict each access?

$\longrightarrow$ Evict and Fill bound the precision of *any* static cache analysis.
Can thus serve as a benchmark for analyses.

Evaluation of Least-Recently-Used

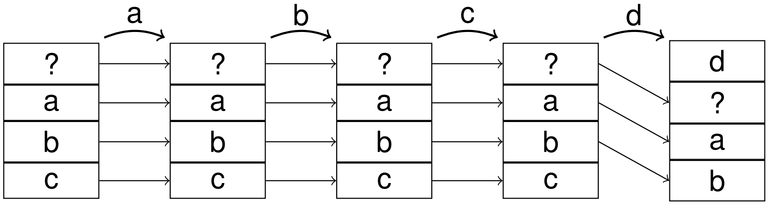
- LRU "forgets" about past quickly:
  - cares about most-recent access to each block only
  - order of previous accesses irrelevant



- In the example: Evict $=$ Fill $=$ 4
- In general: Evict(k) $=$ Fill(k) $=$ k, where k is the associativity of the cache

Evaluation of First-In First-Out (sketch)

- Like LRU in the miss-case
- But: “Ignores” hits



- In the worst-case $k - 1$ hits and k misses: (k = associativity)
  $\longrightarrow \text{Evict}(k) = 2k - 1$
- Another k accesses to obtain complete knowledge:
  $\longrightarrow \text{Fill}(k) = 3k - 1$

Evaluation of Pseudo-LRU (sketch)

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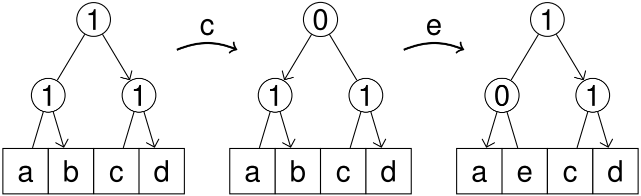
- Tree-bits point to block to be replaced



- Accesses “rejuvenate” neighborhood
  - Active blocks keep their (inactive) neighborhood in the cache
- Analysis yields:
  - $\text{Evict}(k) = \frac{k}{2}\log_2 k + 1$
  - $\text{Fill}(k) = \frac{k}{2}\log_2 k + k - 1$

Evaluation of Policies

Policy	Evict(k)	Fill(k)	Evict(8)	Fill(8)
LRU	k	k	8	8
FIFO	$2k - 1$	$3k - 1$	15	23
MRU	$2k - 2$	$\infty/3k - 4$	14	$\infty/20$
PLRU	$\frac{k}{2}\log_2 k + 1$	$\frac{k}{2}\log_2 k + k - 1$	13	19

- LRU is optimal w.r.t. metrics.
- Other policies are much less predictable.

$\longrightarrow$ Use LRU if predictability is a concern.

- How to obtain *may*- and *must*-information within the given limits for other policies?

Outline

Relative Competitiveness

- Competitiveness (Sleator and Tarjan, 1985):
  worst-case performance of an online policy *relative to the optimal offline policy*
  - used to evaluate online policies
- Relative competitiveness (Reineke and Grund, 2008):
  worst-case performance of an online policy *relative to another online policy*
  - used to derive local and global cache analyses

Definition – Relative Miss-Competitiveness

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Notation

$$m_{\mathbf{P}}(p, s) \quad = \quad \textit{number of misses that policy } \mathbf{P} \textit{ incurs on access sequence } s \in M^* \textit{ starting in state } p \in C^{\mathbf{P}}$$

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Definition (Relative miss competitiveness)

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

$$m_{\mathbf{P}}(p, s) \leq k \cdot m_{\mathbf{Q}}(q, s) + c$$

for all access sequences $s \in M^*$ and cache-set states $p \in C^{\mathbf{P}}, q \in C^{\mathbf{Q}}$ that are compatible $p \sim q$.

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Definition (Competitive miss ratio of **P** relative to **Q**)

The smallest k, s.t. **P** is (k, c)-miss-competitive rel. to **Q** for some c.

Example – Relative Miss-Competitiveness

P is $(3,4)$-miss-competitive relative to **Q**.
If **Q** incurs x misses, then **P** incurs at most $3 \cdot x + 4$ misses.

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If **Q** has x hits, then **P** has at least $\frac{2}{3} \cdot x - 3$ hits.

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Worst: **P** is $(0, 0)$-hit-competitive relative to **Q**.
Analogue to ∞-miss-competitiveness.

Local Guarantees: $(1, 0)$-Competitiveness

Let **P** be $(1, 0)$-competitive relative to **Q**:

$$m_{\mathbf{P}}(p, s) \leq 1 \cdot m_{\mathbf{Q}}(q, s) + 0$$
$$\Leftrightarrow m_{\mathbf{P}}(p, s) \leq m_{\mathbf{Q}}(q, s)$$

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1. If **Q** "hits", so does **P**, and
2. if **P** "misses", so does **Q**.

As a consequence,

1. a *must*-analysis for **Q** is also a *must*-analysis for **P**, and
2. a *may*-analysis for **P** is also a *may*-analysis for **Q**.

Global Guarantees: (k, c)-Competitiveness

Given: Global guarantees for policy **Q**.
Wanted: Global guarantees for policy **P**.

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   $$\mathbf{m_Q(T)}$$

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2. Compute global guarantee for task T under policy **Q**.

   $\mathbf{m_Q(T)}$

3. Calculate global guarantee on the number of misses for **P** using the global guarantee for **Q** and the competitiveness results of **P** relative to **Q**.

   $\mathbf{m_P} \leq \mathbf{k} \cdot \mathbf{m_Q} + \mathbf{c} \quad \mathbf{m_Q(T)} \quad = \quad \mathbf{m_P(T)}$

Relative Competitiveness: Automatic Computation

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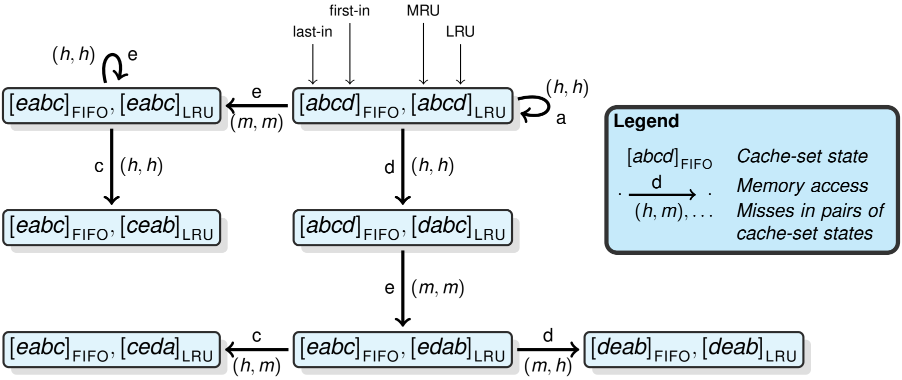
P and **Q** (here: FIFO and LRU) induce transition system:



Competitive miss ratio = maximum ratio of misses in policy **P** to misses in policy **Q** in transition system

Transition System is ∞ Large

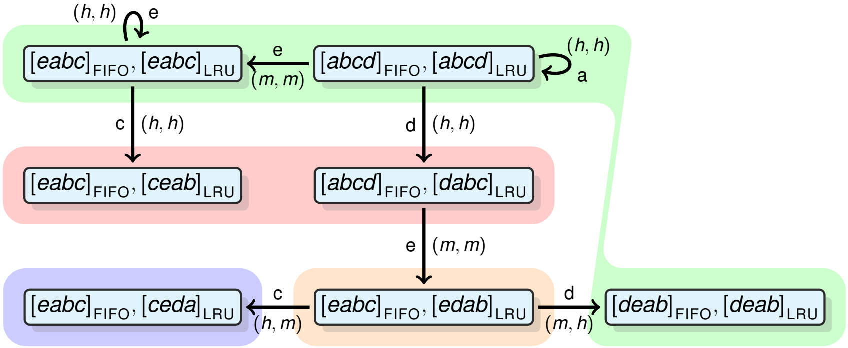
Problem: The induced transition system is ∞ large.

Observation: Only the *relative positions* of elements matter:

$$
\begin{tikzcd}
{[abc]_{\mathrm{LRU}}, [bde]_{\mathrm{FIFO}}} \arrow[r, phantom, "\approx"] \arrow[d, "c"', "{(h, m)}"] & {[fgl]_{\mathrm{LRU}}, [ghm]_{\mathrm{FIFO}}} \arrow[d, "l"', "{(h, m)}"] \\
{[cab]_{\mathrm{LRU}}, [cbd]_{\mathrm{FIFO}}} \arrow[r, phantom, "\approx"] & {[lfg]_{\mathrm{LRU}}, [lgh]_{\mathrm{FIFO}}}
\end{tikzcd}
$$

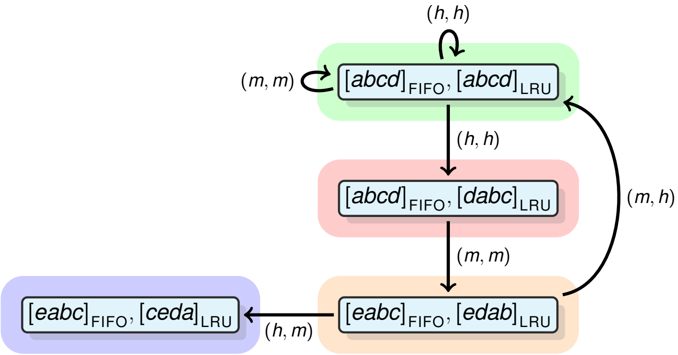
Solution: Construct *finite* quotient transition system.

≈-Equivalent States in Running Example



Finite Quotient Transition System

Merging $\approx$-equivalent states yields a finite quotient transition system:



Competitive Ratio = Maximum Cycle Ratio

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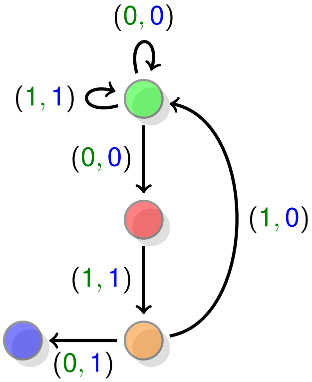

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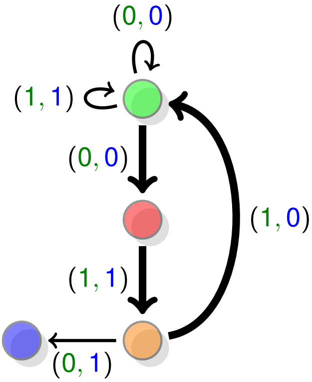

Maximum cycle ratio = $\frac{0+1+1}{0+1+0} = 2$

Tool Implementation

- Implemented in Java, called Relacs
- Interface for replacement policies

- Fully automatic
- Provides example sequences for competitive ratio and constant

- Analysis usually practically feasible up to associativity 8
  - limited by memory consumption
  - depends on similarity of replacement policies

Online version:

`http://rw4.cs.uni-sb.de/~reineke/relacs`

Generalizations

Identified patterns and proved generalizations by hand.

Aided by example sequences generated by tool.

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LRU($2k - 1$) is $(1, 0)$ comp. rel. to FIFO(k), and
LRU($2k - 2$) is $(1, 0)$ comp. rel. to MRU(k).
$\longrightarrow$ LRU-*may*-analysis can be used for FIFO and MRU
$\longrightarrow$ optimal with respect to predictability metric Evict

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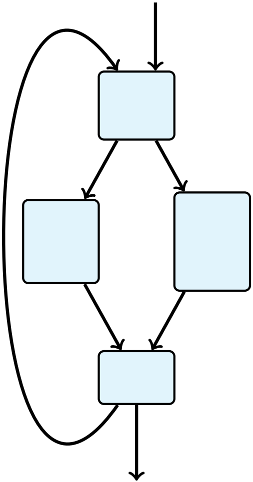
FIFO-*may*-analysis used in the analysis of the branch target buffer of the MOTOROLA POWERPC 56X.

Outline

Measurement-Based Timing Analysis

- Run program on a number of inputs and initial states.
- Combine measurements for basic blocks to obtain WCET estimation.
- Sensitivity Analysis demonstrates this approach may be dramatically wrong.



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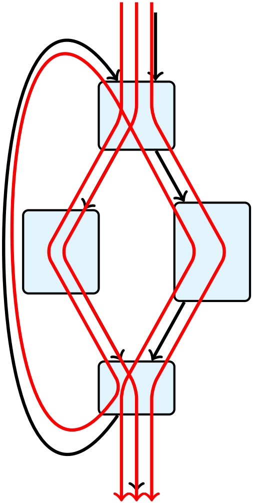
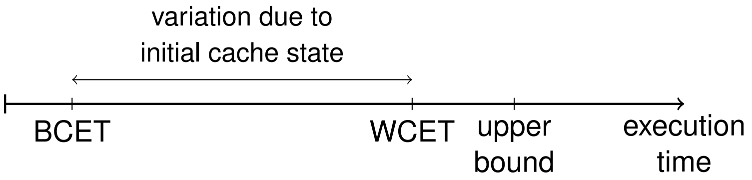


Influence of Initial Cache State



Definition (Miss sensitivity)

Policy **P** is (k, c)-miss-sensitive if

$$m_{\mathbf{P}}(q, s) \leq k \cdot m_{\mathbf{P}}(q', s) + c$$

for all access sequences $s \in M^*$ and cache-set states $q, q' \in C^{\mathbf{P}}$.

Sensitivity Results

Policy	2	3	4	5	6	7	8
LRU	$1,2$	$1,3$	$1,4$	$1,5$	$1,6$	$1,7$	$1,8$
FIFO	$2,2$	$3,3$	$4,4$	$5,5$	$6,6$	$7,7$	$8,8$
PLRU	$1,2$	$-$	∞	$-$	$-$	$-$	∞
MRU	$1,2$	$3,4$	$5,6$	$7,8$	MEM	MEM	MEM

- LRU is optimal. Performance varies in the least possible way.
- For FIFO, PLRU, and MRU the number of misses may vary strongly.
- Case study based on simple model of execution time by Hennessy and Patterson (2003):
  WCET may be 3 times higher than a measured execution time for 4-way FIFO.

Outline

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Summary

Cache Analysis for Least-Recently-Used

. . . efficiently represents sets of cache states by bounding the age of memory blocks from above and below.

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Cousot, P. and Cousot, R. (1977).
Abstract interpretation: a unified lattice model for static analysis of programs by construction or approximation of fixpoints.
In *POPL '77: Proceedings of the 4th ACM SIGACT-SIGPLAN symposium on Principles of programming languages*, pages 238–252, New York, NY, USA. ACM Press.

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Reineke, J., Grund, D., Berg, C., and Wilhelm, R. (2007).
Timing predictability of cache replacement policies.
Real-Time Systems, 37(2):99–122.

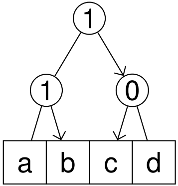
Most-Recently-Used – MRU

MRU-bits record whether line was recently used

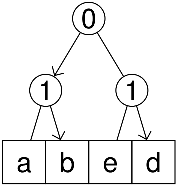
$$\begin{tikzcd}
{[abcd]_{0101}} \arrow[loop right, "b{,}d"] \arrow[d, bend right, "e"'] \\
{[ebcd]_{1101}} \arrow[loop right, "e{,}b{,}d"] \arrow[d, bend right, "c"'] \\
{[ebcd]_{0010}} \arrow[loop right, "c"]
\end{tikzcd}$$

$\longrightarrow$ Never converges

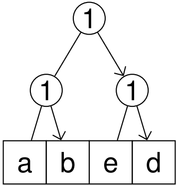
Pseudo-LRU – PLRU



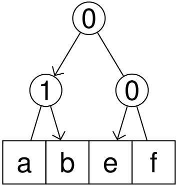
Initial cache-set state $[a, b, c, d]_{110}$.



After a miss on *e*. State: $[a, b, e, d]_{011}$.



After a hit on *a*. State: $[a, b, e, d]_{111}$.



After a miss on *f*. State: $[a, b, e, f]_{010}$.

Hit on *a* “rejuvenates” neighborhood; “saves” *b* from eviction.

May- and Must-Information

$$
\begin{aligned}
May^{\mathbf{P}}(s) &:= \bigcup_{p \in C^{\mathbf{P}}} CC_{\mathbf{P}}(update_{\mathbf{P}}(p, s)) \\
Must^{\mathbf{P}}(s) &:= \bigcap_{p \in C^{\mathbf{P}}} CC_{\mathbf{P}}(update_{\mathbf{P}}(p, s))
\end{aligned}
$$

$$
\begin{aligned}
may^{\mathbf{P}}(n) &:= \left| May^{\mathbf{P}}(s) \right|, \text{where } s \in S^{\neq} \subsetneq M^*, |s| = n \\
must^{\mathbf{P}}(n) &:= \left| Must^{\mathbf{P}}(s) \right|, \text{where } s \in S^{\neq} \subsetneq M^*, |s| = n
\end{aligned}
$$

$S^{\neq}$: set of finite access sequences with pairwise different accesses

Definitions of Metrics

$$\begin{aligned} \mathrm{Evict}^{\mathbf{P}} &:= \min\left\{n \mid may^{\mathbf{P}}(n) \leq n\right\}, \\ \mathrm{Fill}^{\mathbf{P}} &:= \min\left\{n \mid must^{\mathbf{P}}(n) = k\right\}, \end{aligned}$$

where k is **P**'s associativity.

Relation: Pred. Metrics $\leftrightarrow$ Rel. Competitiveness

Let $P(k)$ be $(1, 0)$-miss-competitive relative to policy $Q(l)$, then

(i) $Evict^P(k) \geq Evict^Q(l)$,

(ii) $mls^P(k) \geq mls^Q(l)$.

Alternative Pred. Metrics $\leftrightarrow$ Rel. Competitiveness

Let l be the smallest associativity, such that $\mathrm{LRU}(l)$ is $(1,0)$-miss-competitive relative to $P(k)$. Then

$$\text{Alt-Evict}^{P}(k) = l.$$

Let l be the greatest associativity, such that $P(k)$ is $(1,0)$-miss-competitive relative to $\mathrm{LRU}(l)$. Then

$$\text{Alt-mls}^{P}(k) = l.$$

Size of Transition System

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$$\underbrace{2^{l+l'}}_{\substack{\text{status bits}\\ \text{of } \mathbf{P} \text{ and } \mathbf{Q}}} \cdot \underbrace{\sum_{i=0}^{k} \binom{k}{i}}_{\text{non-empty lines in } \mathbf{P}} \cdot \underbrace{\sum_{i'=0}^{k'} \binom{k'}{i'}}_{\text{non-empty lines in } \mathbf{Q}} \cdot \underbrace{\sum_{j=0}^{\min\{i,i'\}} \binom{i}{j}\binom{i'}{j} j!}_{\substack{\text{number of overlappings}\\ \text{in non-empty lines}}}$$

$$\begin{aligned} \sum_{j=0}^{\min\{k,k'\}} \binom{k}{j}\binom{k'}{j} j! &\leq k! \cdot k'! \sum_{j=0}^{\min\{k,k'\}} \frac{1}{(k-j)!j!(k'-j)!} \\ &\leq k! \cdot k'! \sum_{j=0}^{\infty} \frac{1}{j!} = e \cdot k! \cdot k'! \end{aligned}$$

This can be bounded by

$$2^{l+l'+k+k'} \leq |(C_k^l \times C_{k'}^{l'})/\approx| \leq 2^{l+l'+k+k'} \cdot \underbrace{e \cdot k! \cdot k'!}_{\text{bound on number of overlappings}}$$

Compatible States

$$
\begin{tikzcd}
\boxed{i^{\mathbf{P}} = [\bot\bot\bot\bot]_{\mathbf{P}}} \arrow[d, squiggly, "update_{\mathbf{P}}(i^{\mathbf{P}}, s)"] \arrow[r, phantom, "\approx"] & \boxed{i^{\mathbf{Q}} = [\bot\bot\bot\bot]_{\mathbf{Q}}} \arrow[d, squiggly, "update_{\mathbf{Q}}(i^{\mathbf{Q}}, s)"] \\
\boxed{p} \arrow[r, phantom, "\approx"] & \boxed{q}
\end{tikzcd}
$$

$(1, 0)$-Competitiveness and May/Must-Analyses

Let **P** be $(1, 0)$-competitive relative to **Q**, then

$$\begin{tikzcd}
\boxed{p} \arrow[d, "m_{\mathbf{P}}(p, \langle x \rangle) = 1"'] \arrow[rr, phantom, "\approx"] \arrow[drr, phantom, "\Longrightarrow"] & & \boxed{q} \arrow[d, "m_{\mathbf{Q}}(q, \langle x \rangle) = 1"] \\
\boxed{p'} \arrow[rr, phantom, "\approx"] & & \boxed{q'}
\end{tikzcd}$$

$(1,0)$-Competitiveness and May/Must-Analyses

$$
\begin{tikzcd}
C^{\mathbf{P}} \arrow[r, phantom, "\approx"] \arrow[d, "S"'] & C^{\mathbf{Q}} \arrow[d, "S"] \\
P \arrow[r, phantom, "\approx"] \arrow[d, "\forall p \in P : m_{\mathbf{P}}(p, \langle x \rangle) = 1"'] \arrow[dr, phantom, "\Longrightarrow"] & Q \arrow[d, "\forall q \in Q : m_{\mathbf{Q}}(q, \langle x \rangle) = 1"] \\
P' \arrow[r, phantom, "\approx"] & Q'
\end{tikzcd}
$$

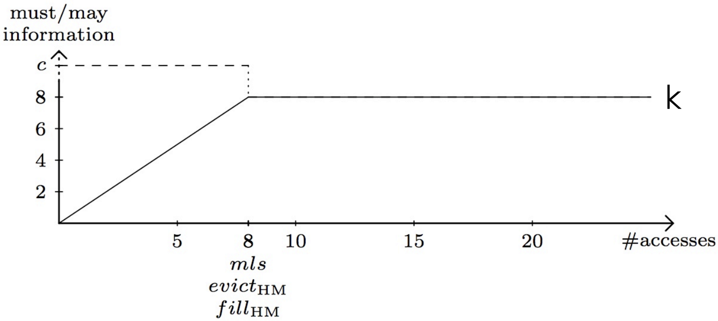
Case Study: Impact of Sensitivity

- Simple model of execution time from Hennessy & Patterson (2003)
- CPI_{hit} = Cycles per instruction assuming cache hits only
- $\frac{\text{Memory accesses}}{\text{Instruction}}$ including instruction and data fetches

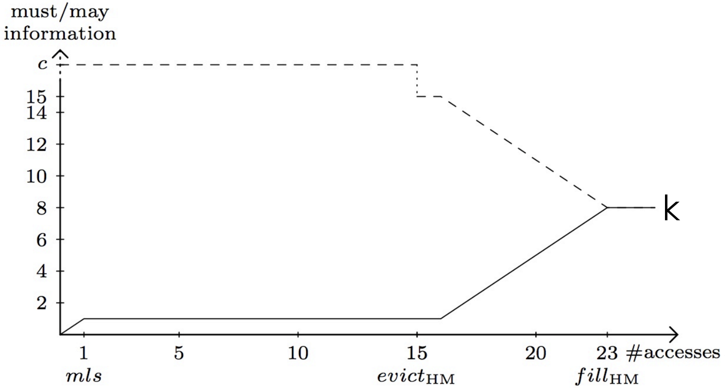
$$\frac{T_{wc}}{T_{meas}} = \frac{\text{CPI}_{hit} + \frac{\text{Memory accesses}}{\text{Instruction}} \times \text{Miss rate}_{wc} \times \text{Miss penalty}}{\text{CPI}_{hit} + \frac{\text{Memory accesses}}{\text{Instruction}} \times \text{Miss rate}_{meas} \times \text{Miss penalty}}$$

$$= \frac{1.5 + 1.2 \times 0.20 \times 50}{1.5 + 1.2 \times 0.05 \times 50} = \frac{13.5}{4.5} = 3$$

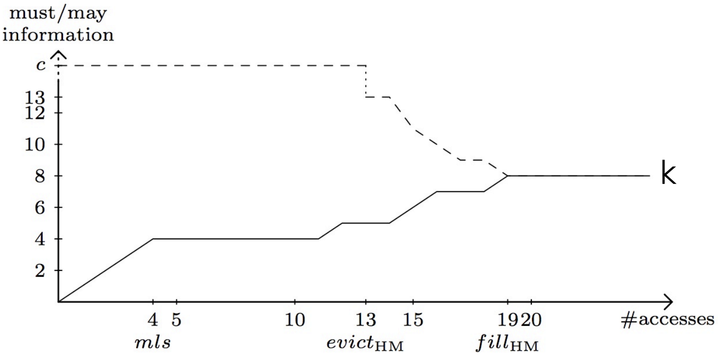
Evolution of May- and Must-Information for LRU



Evolution of May- and Must-Information for FIFO



Evolution of May- and Must-Information for PLRU



Evolution of May- and Must-Information for MRU