Speeding-up exact and fast FIFO-based cache configuration simulation

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Abstract: The number of sets, block size, and associativity determine processor's cache configurations. Particularly in embedded systems, their cache configuration can be optimized since their target applications are much limited. Recently, the CRCB method has been proposed for LRU-based (Least Recently Used-based) cache configuration simulation, which can calculate cache hit/miss counts accurately and very fast changing the three parameters. However many recent processors use FIFO-based (First-In-First-Out-based) caches instead of LRU-based caches due to the viewpoints of their hardware costs. In this paper, we propose a speeding-up cache configuration simulation method for embedded applications that uses FIFO as a cache replacement policy. We first prove several properties for FIFO-based caches and then propose a simulation method that can process two or more FIFO-based cache configurations with different cache associativities simultaneously. Experimental results show that our proposed method can obtain accurate cache hits/misses and runs up to 32% faster than the conventional simulators.

Keywords: FIFO, cache simulation, cache memory, cache configuration optimization, embedded systems

Classification: Electron devices, circuits, and systems

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1 Introduction

Cache memory access speed cannot increase as expected unless the cache is properly configured. Since application programs running on embedded processors are limited unlike those on general-purpose processors, embedded processors can be optimized for a particular application program. Counting cache hits/misses is the important key to configure such an application-driven cache accordingly.

There are roughly two types of cache hit/miss measuring methods: The first ones just estimate cache hit/miss counts based on cache behavior. The second ones simulate memory accesses and obtain cache hit/miss counts accurately. The first ones run very fast but may have large errors in cache hit/miss counts. The second ones are accurate but can be too much time consuming. This paper targets the second approach, a simulation-based approach [3, 6]. Simulating cache hits/misses takes too much time and boosting up the cache configuration simulation is the most important key there.

Cache configuration is parameterized by the number of sets, block size, and associativity. Cache configuration simulation counts cache hits/misses on various cache configurations by changing the three parameters from their minimum values to the maximum. Cache configuration is also characterized by its cache replacement policy, which is an algorithm when and where a datum is stored to and discarded from a cache. LRU-based (Least Recently Used-based) and FIFO-based (First-In-First-Out-based) caches are well seen in practical processors. If a processor uses an LRU-based cache whose associativity is too much large, its hardware cost increases too much. On the other hand, FIFO can be implemented with low hardware cost even if its associativity is large. Many practical processors, such as Power4 processors, use FIFO rather than LRU.

This paper proposes an exact and fast L1 instruction/data cache configuration simulation algorithm for embedded applications that use FIFO as a cache replacement policy. Our algorithm is an improved version of the CSG (cache-set-group) algorithm proposed in [5]. In addition to the cache properties proved in [5], we further prove in this paper several properties for FIFO-based caches and propose a boosting up cache configuration simulation strategy.

2 Cache configuration simulation method

2.1 FIFO-based cache configuration simulation

We assume FIFO as a cache replacement policy. Each *cache set* in a cache is represented by a *priority queue*. In an FIFO-based cache, data in each priority queue are replaced in a first-in-first-out fashion. Cache configuration simulation based on FIFO has a property that priority queues do not have to be updated if cache hit occurs.

Let s_0 and b_0 be the minimum number of cache sets and the minimum block size, respectively. Let s_m , b_m , and a_m be the maximum number of cache sets, the maximum block size, and the maximum associativity, respectively. Then we explore cache configurations (s, b, a) where

$$s = s_0, 2s_0, 4s_0, \dots, s_m \quad (1)$$

$$b = b_0, 2b_0, 4b_0, \dots, b_m \quad (2)$$

$$a = 1, 2, 3, \dots, a_m \quad (3)$$

Given a cache configuration $c = (s, b, a)$, let $S(c, i)$ and $S(c, i)_j$ be the i -th cache set or priority queue on c and the element whose priority is j in $S(c, i)$, where $j = 0, \dots, (a - 1)$, respectively. The tag which is the most IN-side in $S(c, i)$ has the *priority* zero. The tag which is the most OUT-side in $S(c, i)$ has the *priority* $(a - 1)$.

A naive exhaustive algorithm for cache simulation for a particular cache configuration $c = (s, b, a)$ and a particular memory address A is shown in Fig 1 (A). Step 1), Step 3) and Step 4) require a constant time. Step 2) checks one by one a maximum of a elements and then step 2) requires a maximum of a hit/miss *check counts*. We have to repeat Step 1)–Step 4) for all the memory accesses and for all the possible cache configurations.

The CRCB method [6], the very fast cache configuration simulation method, was proposed originally for LRU-based caches, but we proved that the CRCB method can be applied not only to LRU but also to FIFO as well as PLRU (Pseudo-LRU) [5].

2.2 CSG method [5]

In [5], we did not only prove that the CRCB method can be applied to FIFO but also we proposed a totally new method, the CSG method, which performs exact and fast FIFO-based cache configuration simulation.

The CSG method groups several priority queues whose behavior is completely the same and just simulates one of them. Now let us focus on two cache configurations $c_0 = (s, b, a_0)$ and $c_1 = (s, b, a_1)$, where the number s of cache sets is identical, their block size b is also identical, but their associativity is different ($a_0 < a_1$). Let $S(c_0, i)$ and $S(c_1, i)$ be the i -th priority queues on c_0 and c_1 . We assume here that all the tags in $S(c_0, i)$ are included in $S(c_1, i)$ and their priorities are also identical. In this case, we denote $c_0 \subseteq_i c_1$. This mean that c_0 is included in c_1 at the index i . Then we have the following properties [5]:

(A) [Main algorithm of naive exhaustive cache simulation for a cache (s, b, a) and a memory address A]

- 1) Memory address A is partitioned into its tag t , index i , and offset o . Calculate $S(c, i)$ by using c and i .
- 2) Check whether the priority queue $S(c, i)$ contains the tag t or not.
- 3) If $S(c, i)$ contains t in Step 2), a cache hit occurs on c for A and update $S(c, i)$ according to the FIFO replacement policy.
- 4) If $S(c, i)$ does not contain t in Step 2), a cache miss occurs on c for A . Add t into $S(c, i)$ and update it according to the FIFO replacement policy.

(B) [Super-Cache-set-group based cache configuration simulation algorithm]

- 1) Generate a single cache set group including all the cache sets in $SS(i) = \{S(c, i) \mid c \in C(s, b)\}$ for each number of sets s , block size b , and cache set index i .
- 2) For each memory access A , initialize the block size b to be b_0 , the number s of cache sets to be s_0 , and associativity a to be two.
- 3) If we can skip the block size b by applying CRCB-2 [6], go to Step 10).
- 4) Based on CRCB-1 [6], if we have a cache hit for A on $(s, b, 1)$, go to Step 9) since we can skip every cache configuration (s', b, a') where $s' = s, 2s, \dots, s_m$ and $a' = 1, 2, \dots, a_m$.
- 5) Let Q in (s, b, a) be a priority queue that we have to check. If we already know that we have a cache hit on Q , go to Step 7).
- 6) Check whether we have a cache hit on Q .
If a cache hit occurs in Q , we always have a cache hit in (s, b, a') for $a < a'$ in the super cache set group including Q . We can skip cache hit/miss checks for them.
If a cache miss occurs in Q , update Q accordingly and partition the super cache set group into two groups if necessary.
- 7) $a \leftarrow a + 1$. If the new (s, b, a) is within the cache configuration range, go to Step 5).
- 8) $a \leftarrow 2$ and $s \leftarrow 2s$.
If the new (s, b, a) is within the cache configuration range, go to Step 4).
- 9) $s \leftarrow s_0$ and $b \leftarrow 2b$.
If the new (s, b, a) is within the cache configuration range, go to Step 3).
- 10) If there is a next memory access, go to Step 2). Otherwise, stop.

Fig. 1. (A) Main algorithm for naive exhaustive cache simulation and (B) our proposed super-cache-set-group-based cache configuration simulation algorithm (SCSG algorithm).

Property 1. When tag is hit at $S(c_1, i)_j$ and $j < a_0$, we also have a cache hit on c_0 and $c_0 \subseteq_i c_1$ still holds. When tag is hit at $S(c_1, i)_j$ and $a_0 \leq j < a_1$, we have a cache miss on c_0 and we have $c_0 \not\subseteq_i c_1$.

Property 2. When we have a cache miss for tag on c_1 , we also have a cache miss for tag on c_0 but $c_0 \subseteq_i c_1$ still holds true.

We can skip priority queue checking and updating in c_0 by just checking and updating priority queues in c_1 if $c_0 \subseteq_i c_1$.

Based on the above two properties, we proposed in [5] a *cache set group* (CSG) as shown in Fig. 2(A), in which we only simulate the maximum-associativity priority queue and skip the others.

Fig. 2. (A) The priority queues $S(c_1, i)$, $S(c_2, i)$, and $S(c_3, i)$ are in the cache-set-group CSG1. We can skip checking and updating of $S(c_1, i)$ and $S(c_2, i)$ by just checking and updating $S(c_3, i)$. CSG2 only includes a single priority queue. In CSG2, we skip no priority queues. (B) The proposed SCSG algorithm. Since both $S(c_1, i)$ and $S(c_2, i)$ are included in the same super cache set group, we can know that we have a cache hit on $S(c_2, i)$ without actually checking it if we have a cache hit on $S(c_1, i)$. Similarly, if we have a cache hit on $S(c_3, i)$, then we also have a cache hit on $S(c_4, i)$. (C) Combined CSG and SCSG algorithm.

As far as we know, the combined CRCB and CSG methods run the fastest for FIFO-based cache configuration simulation but we can further speed up them as described below.

3 The proposed FIFO-based cache simulation speeding-up Algorithm – SCSG algorithm

In this section, we will apply the property defined in Section 2.2 to FIFO *relaxingly*. Now let us focus on two cache configurations $c_0 = (s, b, a_0)$ and $c_1 = (s, b, a_1)$, where the number s of cache sets is identical, their block size b is also identical, but their associativity is different ($a_0 < a_1$). Let $S(c_0, i)$ and $S(c_1, i)$ be the i -th priority queues on c_0 and c_1 , respectively. We assume here that all the tags in $S(c_0, i)$ are included in $S(c_1, i)$, but their priorities are *not* the same. In this case, we denote $c_0 \tilde{\subset}_i c_1$. This means that c_0 is included *relaxingly* in c_1 at the index i . Even in this situation, we have the following properties for two cache configurations c_0 and c_1 such that $c_0 \tilde{\subset}_i c_1$:

Property 3. When a memory access tag t is hit on c_0 at the index i , it is hit on c_1 and we can skip updating priority queues. In this case $c_0 \tilde{\subset}_i c_1$ still holds.

Proof. All the tags in the priority queue $S(c_0, i)$ are included in a priority queue $S(c_1, i)$. When t is hit on c_0 at the index i , it is also included in c_1 . Both priority queues $S(c_0, i)$ and $S(c_1, i)$ are not updated and $c_0 \tilde{\subset}_i c_1$ still holds. $\square$

Property 4. When a memory access tag t is missed on c_0 and hit on c_1 at the index i , $c_0 \tilde{\subset}_i c_1$ still holds.

Proof. Before updating the priority queue $S(c_0, i)$, $S(c_1, i)$ includes all the tags in $S(c_0, i)$, since $c_0 \tilde{\subset}_i c_1$. When t is missed on c_0 , t is inserted into $S(c_0, i)$. But, since t is hit on c_1 at the index i , $S(c_1, i)$ already includes t . Then $c_0 \tilde{\subset}_i c_1$ still holds after updating the priority queue $S(c_0, i)$. $\square$

Property 5. When a memory access tag t is missed on both c_0 and c_1 at the index i , $c_0 \tilde{\subset}_i c_1$ is not guaranteed to hold.

Proof. When t is missed on $S(c_1, i)$, the largest-priority tag is kicked out of $S(c_1, i)$. Similarly, when t is missed on $S(c_0, i)$, the largest-priority tag is kicked out of $S(c_0, i)$. When the largest-priority tag kicked out of $S(c_1, i)$ is included in $S(c_0, i)$, $c_0 \tilde{\subset}_i c_1$ no longer holds, that is, $c_0 \tilde{\subset}_i c_1$ is not guaranteed to hold in this case. $\square$

Property 3 indicates that, when cache hit occurs on c_0 at the index i , we can skip priority queue checking and updating in c_1 if $c_0 \tilde{\subset}_i c_1$ holds true.

Let $C(s, b) = \{(s, b, a) \mid s \text{ and } b \text{ are fixed and } a = 1, 2, \dots, a_m\}$ be a set of cache configurations whose cache set size and block size are identical but their associativity is different. Let $SS(i) = \{S(c, i) \mid c \in C(s, b)\}$ be a set of cache sets whose index is i in $C(s, b)$. $SS(i)$ is partitioned into several *super cache set groups* (SCSG) $SS(i)_1, SS(i)_2, \dots$ as follows:

- (1) For any cache configuration $c_0 \in C(s, b)$, there exists a group which contains $S(c_0, i)$.
- (2) For any two cache configurations $c_0, c_1 \in C(s, b)$, if $c_0 \tilde{\subset}_i c_1$, $S(c_0, i)$ and $S(c_1, i)$ are in the same group.

Fig. 2 (B) shows an example of super cache set groups. In each super cache set group, if we have a cache hit on a small-associativity priority queue, we also have cache hits on larger-associativity priority queues. We simulate the smaller-associativity priority queues one by one and may skip the larger-associativity priority queues.

Based on the above idea, we naturally propose a super-cache-set-group based algorithm (SCSG algorithm) as shown in Fig 1 (B).

Furthermore, we can apply both the CSG algorithm [5] and the SCSG algorithm proposed above to FIFO. Fig. 2 (C) shows the behavior of the combined CSG and SCSG algorithm. In Fig. 2 (C), let us consider to check a cache hit/miss on SCSG1. We first check a cache hit on CSG1. If there exists a cache-hit priority queue in CSG1, we have cache hits on all the priority queues in CSG2 without really checking them. Further, when we

Table I. Cache configuration simulation time comparisons.

	DineroIV [2]		CRCB [6]		CRCB+CSG [5]	
	CPU time [sec]	Hit/miss check counts	CPU time [sec]	Hit/miss check counts	CPU time [sec]	Hit/miss check counts
ADPCM (E)	244.9 (30.5)	631×10 ⁶	8.04 (1)	65×10 ⁶	7.63 (0.95)	31×10 ⁶
ADPCM (D)	251.7 (31.0)	608×10 ⁶	8.11 (1)	67×10 ⁶	7.69 (0.95)	32×10 ⁶
JPEG (E)	2223.2 (62.3)	30818×10 ⁶	35.7 (1)	3285×10 ⁶	27.2 (0.76)	2282×10 ⁶
JPEG (D)	546.2 (33.7)	3501×10 ⁶	16.2 (1)	809×10 ⁶	13.1 (0.81)	423×10 ⁶
EPIC (E)	3300.8 (29.6)	72963×10 ⁶	111.6 (1)	11968×10 ⁶	91.1 (0.82)	9762×10 ⁶
EPIC (D)	1011.6 (20.5)	12613×10 ⁶	49.4 (1)	4428×10 ⁶	34.1 (0.69)	3068×10 ⁶
G721 (E)	19415.9 (360.9)	136651×10 ⁶	53.8 (1)	4078×10 ⁶	65.8 (1.22)	1904×10 ⁶
G721 (D)	19921.6 (415.0)	139668×10 ⁶	48.0 (1)	3115×10 ⁶	40.2 (0.84)	1449×10 ⁶
Total	46915.9 (141.9)	397457×10 ⁶	330.6 (1)	27819×10 ⁶	286.8 (0.87)	18955×10 ⁶

	CRCB+SCSG		CRCB+CSG+SCSG	
	CPU time [sec]	Hit/miss check counts	CPU time [sec]	Hit/miss check counts
ADPCM (E)	8.04 (1.00)	53×10 ⁶	8.02 (1.00)	31×10 ⁶
ADPCM (D)	8.06 (0.99)	54×10 ⁶	7.98 (0.98)	31×10 ⁶
JPEG (E)	25.5 (0.71)	1815×10 ⁶	27.9 (0.78)	2236×10 ⁶
JPEG (D)	12.4 (0.77)	376×10 ⁶	12.9 (0.80)	415×10 ⁶
EPIC (E)	89.9 (0.81)	9606×10 ⁶	88.0 (0.79)	9205×10 ⁶
EPIC (D)	40.9 (0.83)	3894×10 ⁶	35.1 (0.71)	3052×10 ⁶
G721 (E)	36.7 (0.68)	1014×10 ⁶	42.0 (0.78)	1853×10 ⁶
G721 (D)	35.7 (0.74)	803×10 ⁶	39.4 (0.82)	1362×10 ⁶
Total	257.2 (0.78)	17619×10 ⁶	261.3 (0.79)	18189×10 ⁶

check if a cache hit occurs in CSG1 or not, we check a cache hit on $S(c_2, i)$ first. Based on Property 1, we may skip cache hit/miss check on $S(c_1, i)$.

4 Experimental evaluations

Through the experimental evaluations, we have obtained cache hit/miss counts for (i) Dinero IV [2], (ii) the CRCB method (CRCB), (iii) combined CRCB method and CSG method (CRCB+CSG), (iv) combined CRCB method and our proposed super-cache-set-group based algorithm (CRCB+SCSG), and (v) combined CRCB method, CSG method, and our proposed SCSG method (CRCB+CSG+SCSG). Dinero IV is a well-known standard cache simulator based on an exhaustive approach, which can be applied to FIFO-based caches. All these cache simulation algorithms ran on Xeon 3.0 GHz CPU and 4 GB memory PC. Application programs that we have used here are from MediaBench [4]. We have also used SimpleScalar [1] to obtain memory access histories. We have totally 925 cache configurations whose total cache size ranges from 256 bytes ($s = 32$, $b = 8$ bytes, and $a = 1$) to 134217728 bytes ($s = 1024$, $b = 1$ KB, and $a = 128$).

Table I summarizes the experimental results. Obtained cache hit/miss counts for every cache configuration were exactly the same for Dinero IV, CRCB, CRCB+CSG, CRCB+SCSG, and CRCB+CSG+SCSG. Roughly saying, CRCB+SCSG and CRCB+CSG+SCSG run on average 22% and 21% faster, respectively, than CRCB. CRCB+SCSG and CRCB+CSG+SCSG run on average 10% and 9% faster than CRCB+CSG, respectively. CRCB+SCSG runs 2% faster than CRCB+CSG+SCSG. This may be due to the overheads of combining CSG and SCSG. Overall, introducing the SCSG algorithm leads to the world fastest FIFO-based cache configuration simulation.

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