**Comparison of Database Buffer Management Algorithms – 2Q and CLOCK-Pro**

Ashish Walia

Department of Computer Science

Courant Institute of Mathematical Sciences

New York University

[ashish.walia@nyu.edu](mailto:ashish.walia@nyu.edu)

Dennis Shasha

Department of Computer Science

Courant Institute of Mathematical Sciences

New York University

[shasha@cs.nyu.edu](mailto:shasha@cs.nyu.edu)

June 04, 2012

1. **Introduction**

Database management systems (DBMSs) typically maintain a database buffer to provide high speed access to database pages. A database buffer consists of page frames of the size of disk blocks which are copied from disk into buffer without any change in format [1]. Since it’s more expensive to access a database page from disk than to access a page from the buffer [2], the main challenge is to effectively manage pages in the buffer. Finding an efficient solution for database buffer management is a well-researched problem. Many algorithms have been proposed so far in the same context, such as LRU, LIRS, Clock-Pro, 2Q, CAR, ARC etc. In this report, our focus is restricted to comparing 2Q and CLOCK-Pro algorithms in terms of hit rate (ratio of number of pages requested that are already in the buffer to the total number of pages requested) over a series of real-time workloads.

1. **Optimal Page Replacement Algorithm (OPT)**

The optimal page replacement algorithm or clairvoyant algorithm replaces a page whose next access will be farthest in future [3]. It’s impossible to implement OPT algorithm in reality because the point when a page will be referenced next in the future is not known in advance [3]. However, OPT gives a natural best case among all the page replacement algorithms and can be used as a standard point of reference against which to compare performance of other page replacement algorithms. Our experiments were based on memory traces; hence we could easily look ahead in the future to see which page would be accessed farthest in the future. We used that information in our OPT algorithm implementation.

On accessing a page X :

begin

if X is in the buffer then

increment page hit counter

else // X not in the buffer

increment page miss counter

if buffer is not full then

add X to the buffer

else // buffer is full

//Select a page that will not be referenced in the future for the / //longest time

page Y:=selectPageForEviction()

remove Y from the buffer

end if

end if

end

\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_

selectPageForEviction()

begin

create a sub list, SL, of all the pages that have not been accessed so far

//iterate over all the pages present in buffer

for i in 1..buffer.length loop

page X := buffer(i)

//calculate when a page will be accessed next time in the future

X.next\_reference\_time:=SL.indexOf(X.pageNum)

//if the page is not referenced in the future

if X.next\_reference\_time==-1 then

//this page is the ideal candidate for page eviction

return X

end if

end loop

//page with the highest value of next\_reference\_time will be selected for eviction

page Y:= buffer(1)

for i in 1..buffer.length loop

page X := buffer(i)

if X. next\_reference\_time > Y. next\_reference\_time then

Y:=X

end if

end loop

return Y

end

1. **Two Queue Page Replacement Algorithm (2Q)**

2Q maintains two families of queues: hot and cold. When a page is referenced for the first time, 2Q places it in the “cold” A1 queue, managed as FIFO (first-in first-out) queue [4]. If the page is accessed again while in the A1 queue, then it’s probably a hot page and is promoted to “hot” Am queue, a queue managed as a LRU (least-recently-used) queue [4]. If the page is not accessed while in the cold queue, then it’s eventually removed from the cold queue [4]. 2Q deals with the problem of correlated references by further dividing the A1 queue into A1in (of maximum size Kin) and A1out (of maximum size Kout) queues [4]. The A1in queue holds newly referenced pages whereas the A1out queue keeps track of pointers to pages (but not the pages themselves) that have high long-term access rates [4]. Kin and Kout parameters are tuning parameters and set to fixed percentages of the cache size In our experiments, Kin = 20% or memory size and Kout = 65% of memory size works well as does Kin = 25% of memory size and Kout = 60% of memory size with the remaining memory devoted to Am.” [Ashish, in the 2Q paper we recommend different numbers. Kin as 25% and Kout as 50%. Also, it’s important to note that the pages in Aout are no longer in memory (second column of 441). We keep only the pointers in memory which take negligible space which you can assume is 1% of what a normal page takes. Thus the rest of memory (74.5% of it roughly goes to Am). So, let me check your actual code again.]

**Pseudo code of 2Q algorithm as described in [4]:**

On Accessing a Page X:

begin

        if X is in Am then

            Move X to the head of Am // treating Am as an LRU queue

        else if X is in A1out then

            reclaimfor(X) // find a page slot for X that is already free or from A1in if full

// or from Am if A1in is not full but Am has taken all the rest of the

// memory.

                Add X to the head of Am

        else if X is in A1in  
                //do nothing

        else

                  reclaimfor(X) // as above

                  Add X to the head of A1in

        end if

end

\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_

//If there is space, we give it to X.

//If there is no space, we free a page slot to make room for page X

// either from A1in or Am depending on which one has exceeded its space allotment.

// Regardless of whether X ultimately goes to Am or A1in, we may take a page slot from

// A1in or Am if there are no free slots. For example, if will ultimately add to Am, but both

// A1in and Am are full, then we will take the page from A1in. If A1in is not full, then we

// will take the page from Am because it must have too much. The same holds if we

// ultimately add to A1in. The goal, when there are no

// free slots, is to keep A1in at its maximum size.

reclaimfor(page X)

begin

        if there are free page slots then

                   put X into a free page slot

        else if (|A1in|> Kin) [Ashish: leave as it is in 2q]

                    page out the tail of A1in, call it Y

                    add identifier of Y to the head of A1out

                   if (|A1out|>Kout)

                    remove identifier of Z from the tail of A1out

                    end if

                    put X into the reclaimed page slot

        else

                    page out the tail of Am, call it Y

                   //do not put Y’s pointer on A1out, it has not been accessed for a while

                    put X into the reclaimed page slot

        end if

end

1. **CLOCK-Pro Page Replacement Algorithm**

In [5], S. Jiang, F. Chen and X. Zhang describes reuse distance as the period of time in terms of the number of other distinct pages accessed since its last access. CLOCK-Pro uses reuse distance to categorize a page as either a hot page or a cold page [5]. A page is categorized as a hot page if it has a small reuse distance or as a cold page if it has large reuse distance [5]. CLOCK-Pro algorithm maintains a single circular list where all hot and cold pages are placed in the order of their accesses [5]. Hot pages are placed at the tail of the list whereas cold pages are placed at the head of the list [5].

Once a cold page is added to the list, it’s assigned a test period so that it gets a fair chance to compete with other hot pages in the list [5].

We have assumed that the testing period of a cold page p is at least equal to the time it takes for mc new cold pages to be added to the cache before the cold page p is re-accessed. In the non-adaptive version of the algorithm, the number of hot and cold pages, mh and mc, respectively, is fixed, where m = mh + mc is the cache size. We chose mh = 95% of the cache size and mc = 5% of the cache size in our experiments. [*These parameter values were provided by default in the source files that Dr. Song Jiang provided to us*]. The circular list caches mh hot pages, mc cold pages and history access information of at most m non-resident cold pages. There are flags associated with each page which indicate whether a page is a hot page or a cold page, a page is in clock or out of clock, and a page is resident or non-resident. There is another flag which indicates if the cold page is in the test period. Additionally, the algorithm maintains a reference bit for each page and three hands or pointers to the pages in the list, namely, HANDcold, HANDhot and HANDtest.

HANDcold points to the last resident cold page in the list i.e the farthest cold page from the head of the list. It’s used to search for the cold page to replace. While searching for the cold page to replace, if the page pointed to by HANDcold is in the test period and has reference bit set as 0, the resident cold page is turned into a non-resident cold page. If cold page is not in the test period and has reference bit set as 0, it’s removed from the clock. However, if the page pointed to by HANDcold has reference bit set as 1 and is in the test period, the page is turned into a hot page, its reference bit is reset and it’s moved to the head of the list. HANDhot is triggered to perform its actions. If the page pointed to by HANDcold is not in the test period but has its reference bit set as 1, then its reference bit is reset and it’s moved to the head of the list.

HANDhot points to the tail of the list i.e. the last hot page in the list. It’s triggered when a cold page is accessed in its test period and is turned into a hot page. If the hot page pointed to by HANDhot has reference bit set as 1, its reference bit is reset and it’s moved to the head of the list. HANDhot is moved a page forward in the clockwise direction and the same process is repeated for all the other hot pages until a hot page with reference bit set as 0 is encountered by HANDhot. In such a case, the hot page is turned into a cold page and is moved to the head of the list. Another interesting point to note about movement of HANDhot is that if a cold page is encountered by the HANDhot and the cold page is in its test period, then its test period is terminated and it’s removed from the clock. In the end, HANDhot stops at a hot page.

If the number of non-resident cold pages exceeds m, then the test period of the cold page pointed to by HANDtest is terminated. If the cold page pointed to by HANDtest is a non-resident cold page, then it’s also removed from the clock.

When a page fault occurs and clock (circular list) is empty, it is first filled with mh hot pages and then with mc cold pages. If page fault occurs and clock is full, HANDcold is run to create free space in the clock for the faulted page. The faulted page is set as a cold page, moved to the head of the list and its test period is initiated. However, if a page fault occurs and the faulted page is a non-resident cold page, it is turned into a hot page and is moved to the head of list. HANDhot is also run to turn a hot page with largest recency into a cold page.

More about CLOCK-Pro algorithm i.e. the adaptive version of the algorithm, is explained in [5]. [Ashish: now I’m confused. Are we using the adaptive or non-adaptive version.]

1. **Experiments**

**5.1. Simulation on file I/O traces**

The file I/O traces used in this section are same as used for evaluation of the CLOCK-Pro algorithm in [5]. Quoting from [5]:

* + 1. **cpp** is a GNU C compiler pre-processor trace and is a member of the probabilistic pattern group.
    2. **multi2** is a member of the mixed pattern group and is obtained by executing three workloads, namely, cs, cpp and postgres, together.
    3. **sprite** is a Sprite network file system trace which contains requests to a file server from client workstations for a two-day period. It’s a member of temporally-clustered pattern group.
    4. **glimpse** is a text information utility trace and is a member of the loop pattern group.

For workload cpp, the performance of 2Q and CLOCK-Pro are comparable (see Table 1). Clock-PRO performs significantly better than 2Q for workloads multi2 and glimpse (see Table 2 and Table 4). However, for the sprite workload, the hit ratio of the 2Q algorithm is higher than CLOCK-Pro algorithm (see Table 3).

|  |  |  |  |
| --- | --- | --- | --- |
| **Cache Size** | **2Q (Kin = 25% Kout=65%)** | **CLOCK-Pro** | **OPT** |
| 100 | .790 | .771 | .825 |
| 500 | .861 | .860 | .865 |
| 1000 | .865 | .864 | .865 |
| 2000 | .865 | .865 | .865 |
| 3000 | .865 | .865 | .865 |
| 4000 | .865 | .865 | .865 |
| 5000 | .865 | .865 | .865 |

**Table 1:** Hit Rate of 2Q, CLOCK-Pro and OPT algorithms on workload cpp.

|  |  |  |  |
| --- | --- | --- | --- |
| **Cache Size** | **2Q (Kin = 25% Kout=65%)** | **CLOCK-Pro** | **OPT** |
| 100 | .259 | .266 | .354 |
| 500 | .392 | .495 | .536 |
| 1000 | .506 | .567 | .621 |
| 2000 | .688 | .702 | .746 |
| 3000 | .767 | .778 | .784 |
| 4000 | .784 | .782 | .784 |
| 5000 | .784 | .784 | .784 |
| 6000 | .784 | .784 | .784 |
| 7000 | .784 | .784 | .784 |
| 8000 | .784 | .784 | .784 |
| 10000 | .784 | .784 | .784 |
| 20000 | .784 | .784 | .784 |

**Table 2:** Hit Rate of 2Q, CLOCK-Pro and OPT algorithms on workload multi2.

|  |  |  |  |
| --- | --- | --- | --- |
| **Cache Size** | **2Q (Kin = 25% Kout=65%)** | **CLOCK-Pro** | **OPT** |
| 100 | .366 | .280 | .508 |
| 500 | .857 | .768 | .879 |
| 1000 | .924 | .884 | .932 |
| 2000 | .942 | .923 | .948 |
| 3000 | .946 | .932 | .947 |
| 4000 | .947 | .937 | .947 |
| 5000 | .947 | .941 | .947 |
| 6000 | .947 | .943 | .947 |
| 7000 | .947 | .947 | .947 |
| 8000 | .947 | .947 | .947 |
| 10000 | .947 | .947 | .947 |
| 20000 | .947 | .947 | .947 |

**Table 3:** Hit Rate of 2Q, CLOCK-Pro and OPT algorithms on workload sprite.

|  |  |  |  |
| --- | --- | --- | --- |
| **Cache Size** | **2Q (Kin = 25% Kout=65%)** | **CLOCK-Pro** | **OPT** |
| 100 | .009 | .058 | .077 |
| 500 | .012 | .319 | .343 |
| 1000 | .461 | .501 | .531 |
| 2000 | .579 | .580 | .579 |
| 3000 | .579 | .580 | .579 |
| 4000 | .579 | .580 | .579 |
| 5000 | .579 | .580 | .579 |

**Table 4:** Hit Rate of 2Q, CLOCK-Pro and OPT algorithms on workload glimpse.

**5.2 Simulation on an Online Transaction Processing (OLTP) workload**

The I/O traces used in this section are obtained from [5]. These traces are from OLTP applications running at two large financial institutions as mentioned in [5]. We had to tweak the original implementation of CLOCK-PRO algorithm provided by Dr. Song Jiang, in order to execute it successfully on Finanical1.spc. We had experienced segmentation fault error upon running CLOCK-Pro algorithm on the Financial.spc trace and had to change the page table implementation from array to map in the original source code. We recorded a slightly better performance of the 2Q algorithm compared with the CLOCK-Pro algorithm for OLTP workload (see Table 5 and Table 6).

|  |  |  |  |
| --- | --- | --- | --- |
| **Cache Size** | **2Q (Kin = 30% Kout=60%)** | **CLOCK-Pro** | **OPT** |
|  |  |  |  |
|  |  |  |  |
| 500000 | .867 | .839 | .867 |
| 1000000 | .867 | .867 | .867 |
| 2000000 | .867 | .867 | .867 |
| 3000000 | .867 | .867 | .867 |

**Table 5:** Hit Rate of 2Q, CLOCK-Pro and OPT algorithms on workload Financial1.spc.

|  |  |  |  |
| --- | --- | --- | --- |
| **Cache Size** | **2Q (Kin = 30% Kout=60%)** | **CLOCK-Pro** | **OPT** |
|  |  |  |  |
|  |  |  |  |
| 500000 | .920 | .920 | .920 |
| 1000000 | .920 | .920 | .920 |
| 2000000 | .920 | .920 | .920 |
| 3000000 | .920 | .920 | .920 |

**Table 6:** Hit Rate of 2Q, CLOCK-Pro and OPT algorithms on workload Financial2.spc.

1. **Sensitivity of Parameters**

**6.1 2Q**

Choosing a value for Kin and Kout parameter for 2Q algorithm is essentially a tuning task. We experimented with different values of Kin and Kout parameters (see Table 7, Table 8, Table 9 and Table 10) and noted that Kin = 20% and Kout=60% did reasonalbly well for cpp and glimpse workloads whereas Kin = 25% and Kout=65% of cache size did well for multi2and sprite traces.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Cache Size** | **2Q**  **(Kin = 30%**  **Kout=60%)** | **2Q**  **(Kin = 20%**  **Kout=60%)** | **2Q**  **(Kin = 25%**  **Kout=60%)** | **2Q**  **(Kin = 25%**  **Kout=65%)** | **2Q**  **(Kin = 30%**  **Kout=65%)** |
| 100 | .783 | .795 | .789 | .790 | .785 |
| 500 | .861 | .861 | .861 | .861 | .861 |
| 1000 | .865 | .865 | .865 | .865 | .865 |
| 2000 | .865 | .865 | .865 | .865 | .865 |
| 3000 | .865 | .865 | .865 | .865 | .865 |
| 4000 | .865 | .865 | .865 | .865 | .865 |
| 5000 | .865 | .865 | .865 | .865 | .865 |

**Table 7:** Hit Rate of 2Q algorithm with different values of Kin and Kout on cpp workload.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Cache Size** | **2Q**  **(Kin = 30%**  **Kout=60%)** | **2Q**  **(Kin = 20%**  **Kout=60%)** | **2Q**  **(Kin = 25%**  **Kout=60%)** | **2Q**  **(Kin = 25%**  **Kout=65%)** | **2Q**  **(Kin = 30%**  **Kout=65%)** |
| 100 | .252 | .257 | .254 | .259 | .259 |
| 500 | .391 | .391 | .391 | .392 | .392 |
| 1000 | .506 | .506 | .506 | .506 | .506 |
| 2000 | .678 | .700 | .688 | .688 | .678 |
| 3000 | .761 | .773 | .767 | .766 | .760 |
| 4000 | .784 | .784 | .784 | .784 | .784 |
| 5000 | .784 | .784 | .784 | .784 | .784 |
| 6000 | .784 | .784 | .784 | .784 | .784 |
| 7000 | .784 | .784 | .784 | .784 | .784 |
| 8000 | .784 | .784 | .784 | .784 | .784 |
| 10000 | .784 | .784 | .784 | .784 | .784 |
| 20000 | .784 | .784 | .784 | .784 | .784 |

**Table 8:** Hit Rate of 2Q algorithm with different values of Kin and Kout parameters on multi2 workload.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Cache Size** | **2Q**  **(Kin = 30%**  **Kout=60%)** | **2Q**  **(Kin = 20%**  **Kout=60%)** | **2Q**  **(Kin = 25%**  **Kout=60%)** | **2Q**  **(Kin = 25%**  **Kout=65%)** | **2Q**  **(Kin = 30%**  **Kout=65%)** |
| 100 | .357 | .364 | .361 | .366 | .363 |
| 500 | .854 | .857 | .856 | .857 | .855 |
| 1000 | .922 | .924 | .923 | .924 | .924 |
| 2000 | .942 | .942 | .942 | .942 | .942 |
| 3000 | .945 | .945 | .944 | .946 | .946 |
| 4000 | .947 | .947 | .947 | .947 | .947 |
| 5000 | .947 | .947 | .947 | .947 | .947 |
| 6000 | .947 | .947 | .947 | .947 | .947 |
| 7000 | .947 | .947 | .947 | .947 | .947 |
| 8000 | .947 | .947 | .947 | .947 | .947 |
| 10000 | .947 | .947 | .947 | .947 | .947 |
| 20000 | .947 | .947 | .947 | .947 | .947 |

**Table 9:** Hit Rate of 2Q algorithm with different values of Kin and Kout parameters on sprite workload.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Cache Size** | **2Q**  **(Kin = 30%**  **Kout=60%)** | **2Q**  **(Kin = 20%**  **Kout=60%)** | **2Q**  **(Kin = 25%**  **Kout=60%)** | **2Q**  **(Kin = 25%**  **Kout=65%)** | **2Q**  **(Kin = 30%**  **Kout=65%)** |
| 100 | .009 | .009 | .009 | .009 | .009 |
| 500 | .012 | .012 | .012 | .012 | .012 |
| 1000 | .444 | .477 | .460 | .460 | .444 |
| 2000 | .579 | .579 | .579 | .579 | .579 |
| 3000 | .579 | .579 | .579 | .579 | .579 |
| 4000 | .579 | .579 | .579 | .579 | .579 |
| 5000 | .579 | .579 | .579 | .579 | .579 |

**Table 10:** Hit Rate of 2Q algorithm with different values of Kin and Kout parameters on glimpse workload.

*Kin = 20% and Kout=60% did reasonalbly well for cpp and glimpse workloads whereas Kin = 25% and Kout=65% of cache size did well for multi2and sprite traces.--Ashish*

[Could you see whether there is one setting for Kin/Kout for all workloads that worked well?]

**6.2 CLOCK-Pro**

The mh and mc parameters decide number of hot and cold pages in the cache in the CLOCK Pro algorithm. We have chosen mh as 95% and mc as 5% of the cache size in our experiments. [*These parameter values were provided by default in the source files that Dr. Song Jiang provided to us*]. Another important parameter worth consideration is the testing period. Based on our analysis, it’s safer to assume that testing period of a cold page p is at least equal to the time it takes for mc new cold pages to be added to the cache before the cold page p is re-accessed. [Is this the adaptive algorithm?]

1. **Conclusion**

CLOCK-Pro and 2Q give comparable performance in all cases of interest. The differences are rarely more than 1 or 2%. Based on these experiments, we would recommend the use of whichever algorithm is easier to implement.

1. **Acknowledgements**

Many thanks to Dr. Song Jiang for providing us source code for CLOCK-Pro algorithm and memory traces used in [5]. We are also thankful to Laboratory of Advanced Systems Software, University of Massachusetts, Amherst, for making OLTP traces available on the web [6] courtesy of Ken Bates from HP, Bruce McNutt from IBM and the Storage Performance Council.

1. **References**

[1] J. M. Hellerstein, M. Stonebraker and J. Hamilton. Architecture of Database System.

[2] W. Effelsberg and T. Haerder. Principles of Database Buffer Management.

[3] OPT, <http://en.wikipedia.org/wiki/Page_replacement_algorithm>

[4] T. Johnson and D. Shasha. 2Q: A Low Overhead High Performance Buffer

Management Replacement Algorithm. In Proc. of VLDB’94, 1994, pp 439-450.

[5] S. Jiang, F. Chen and X. Zhang. CLOCK-Pro: An Effective Improvement of the Clock

Replacement. In Proc. of USENIX’05, April 2005.

[6] UMASSTraceRepository, <http://traces.cs.umass.edu/index.php/Storage/Storage>